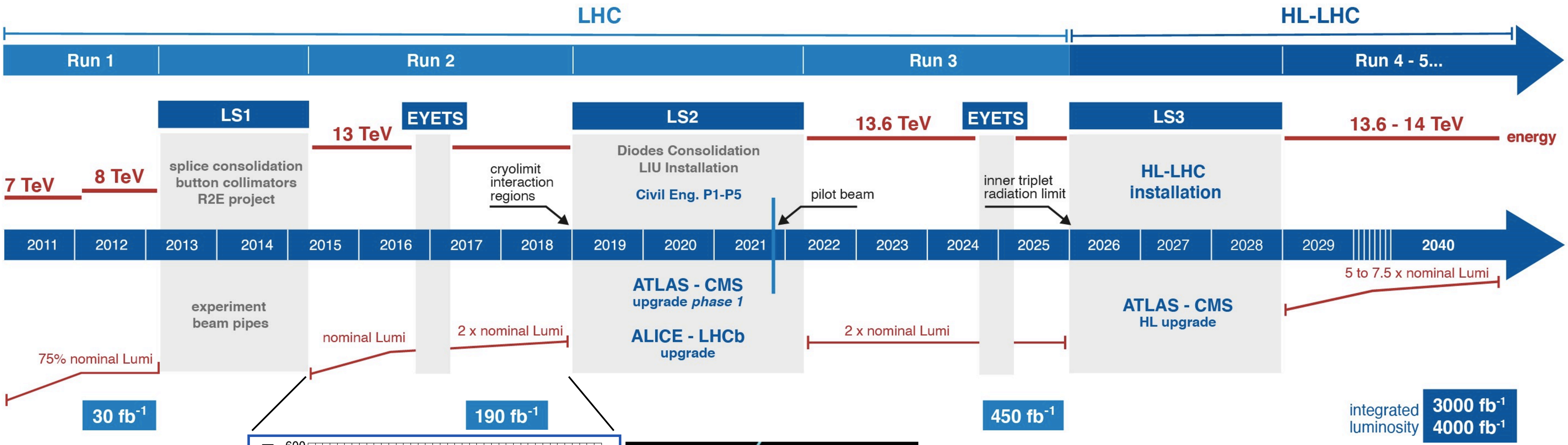
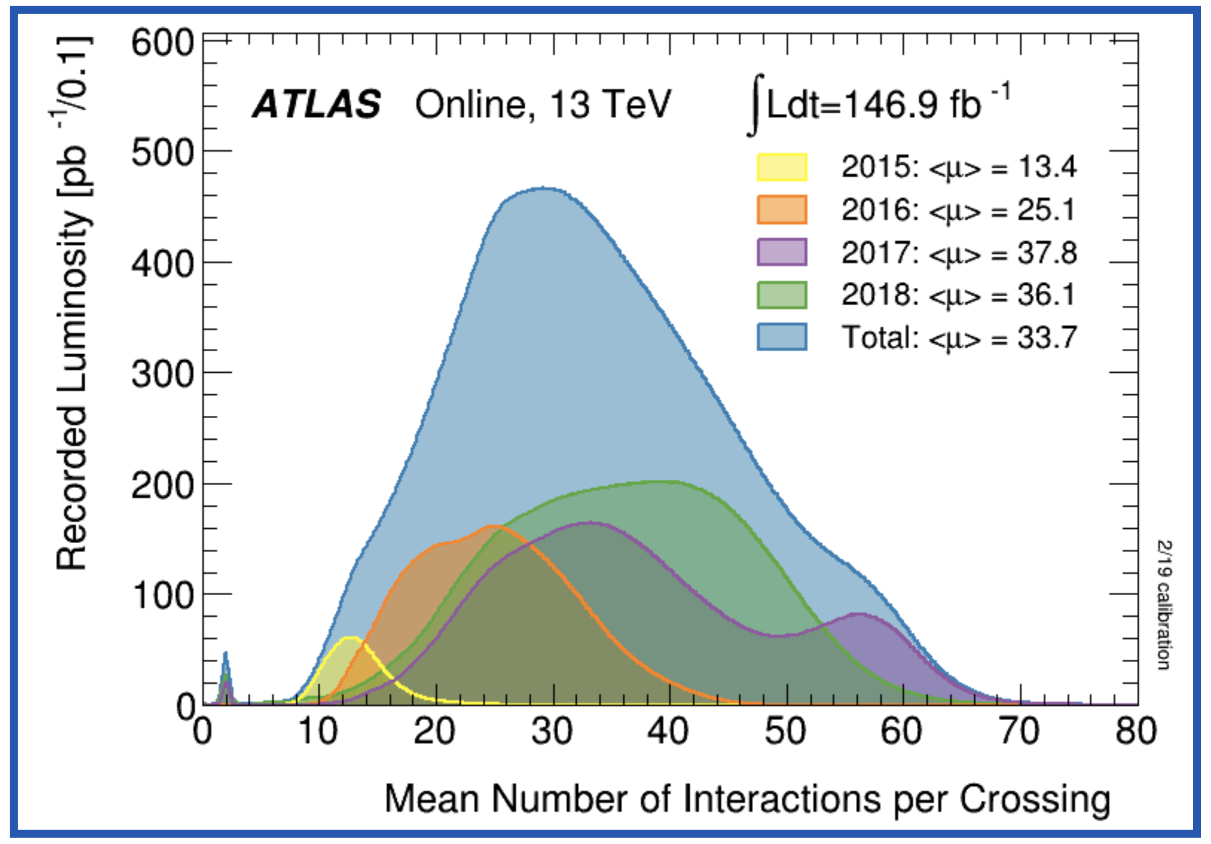
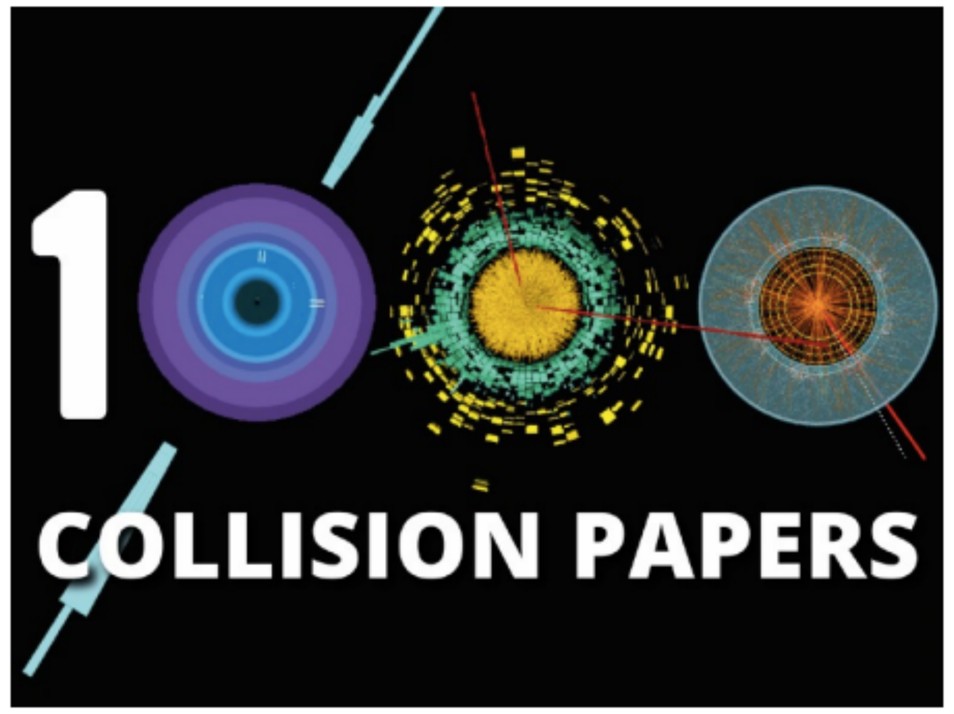
Top quark physics at ATLAS experiment

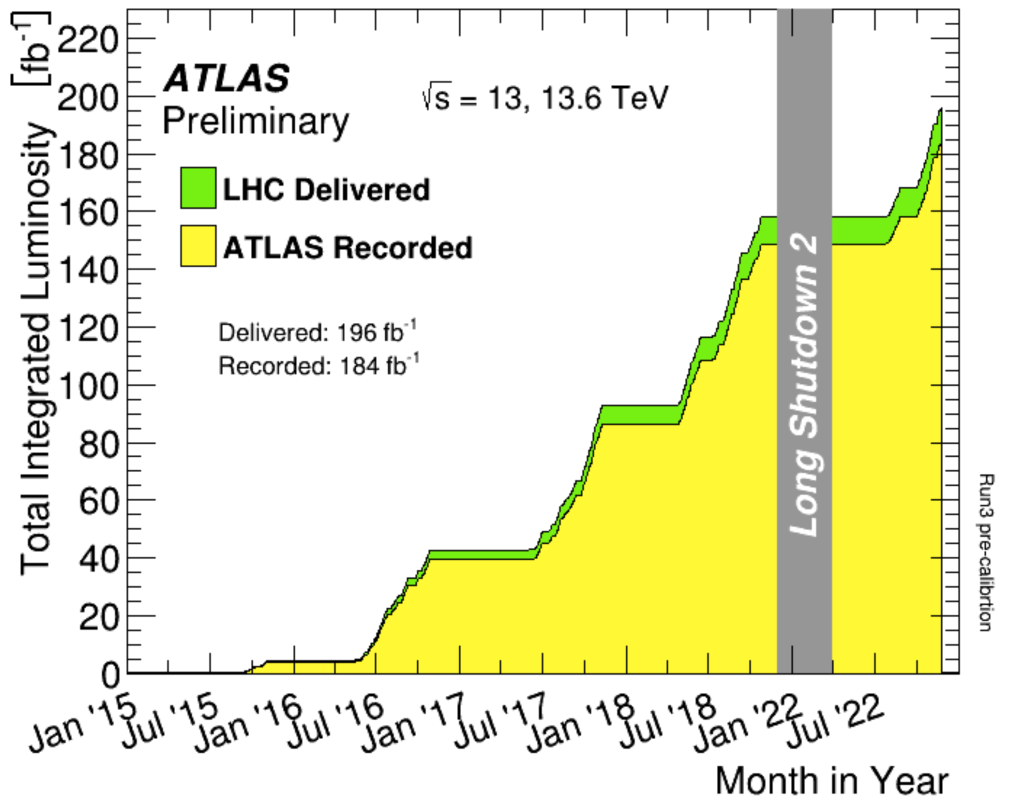
Jiri Hejbal (Institute of Physics in Prague)

LHC / HL-LHC Plan





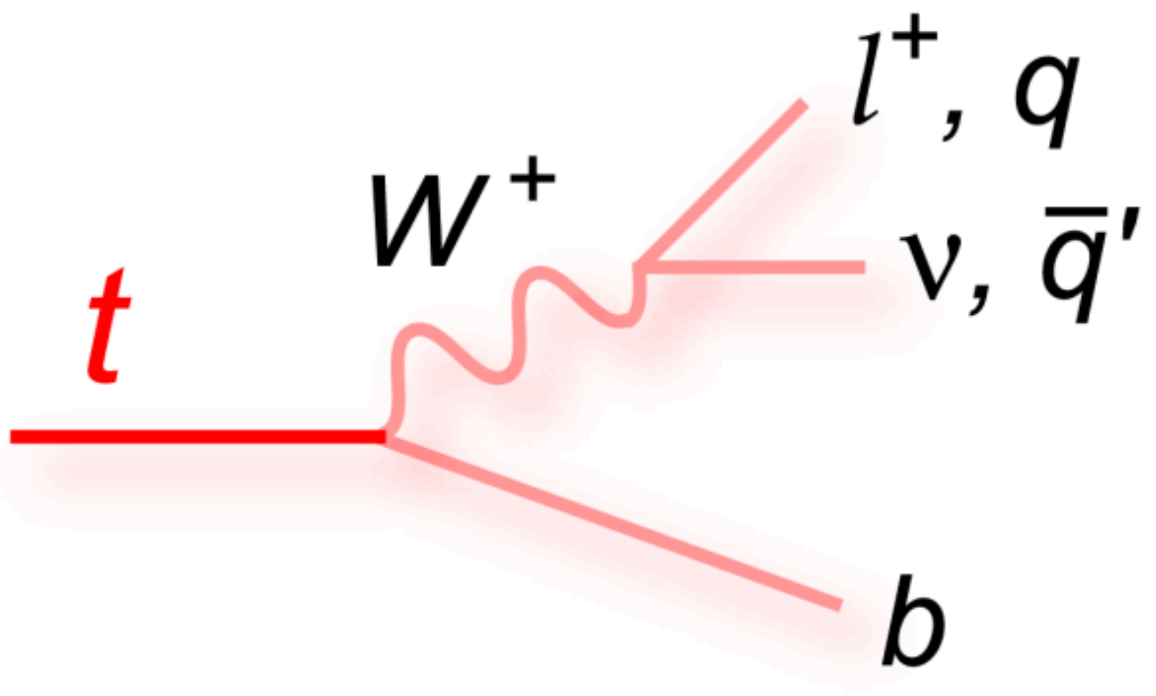


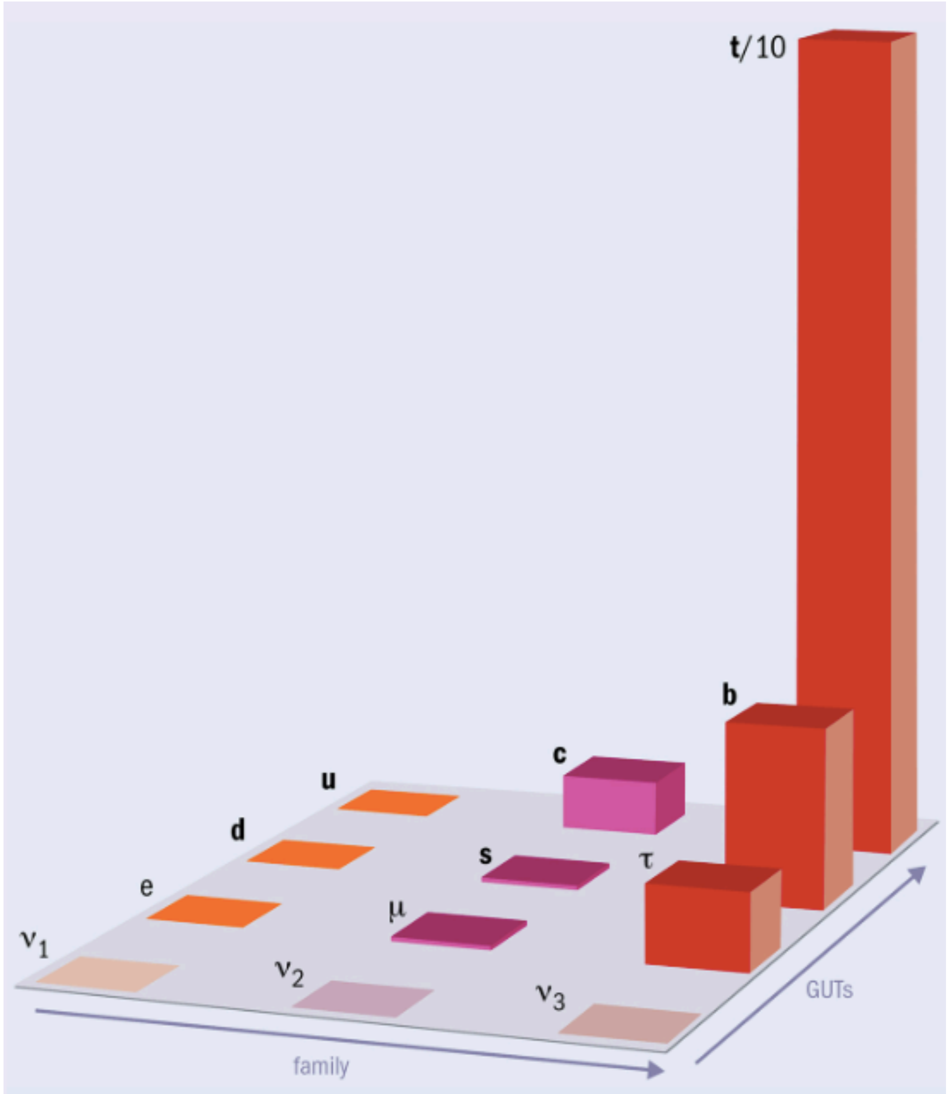


Top quark - introduction

- A unique particle
  - The heaviest known elementary particle
  - Unique properties from experimental and theoretical side
- Very short lifetime
  - The only quark which does not hadronizes
  - Properties studies via its decay products
- It has a significant impact on cosmological models (e.g. determinaton of the lifetime of the Universe)

PhysRevD.97.056006



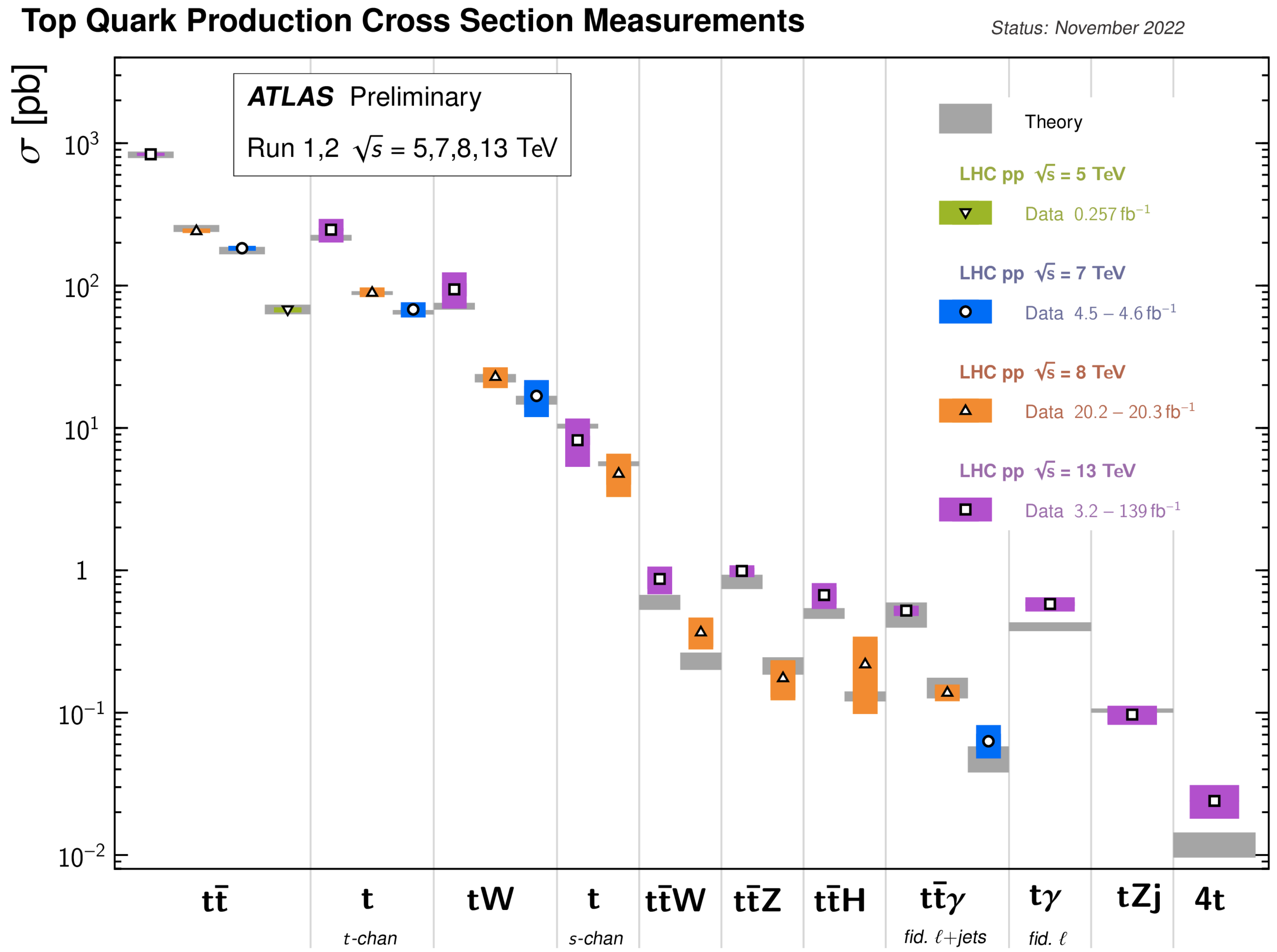


CERN Courier

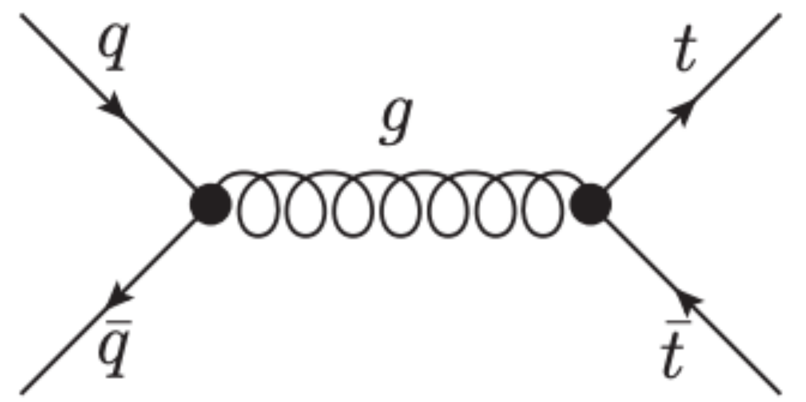
Top quark physics at the LHC

- **Two main production modes:**
  - pair production ($t\bar{t}$) - mainly via strong interaction
    - Run 2 produced ~200M top pairs in ATLAS+CMS at 13 TeV!
  - single top - electroweak interactions

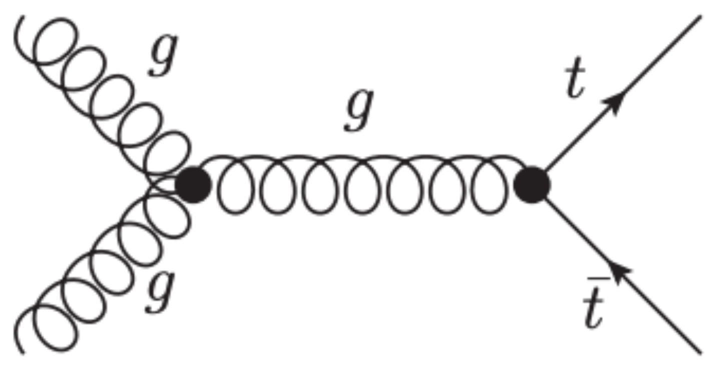
- **Top quarks physics important for many reasons:**
  - Precision test of the Standard Model
  - Sensitivity to new physics beyond the Standard Model
  - PDF fits - especially can contribute to high-x for gluon PDF
  - Parameters of MC generators



tt pairs production

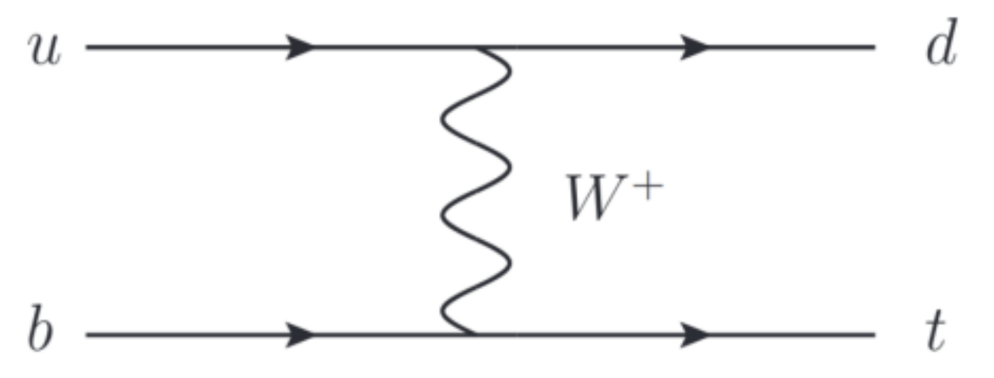


quark-antiquark annihilation



gluon-gluon fusion

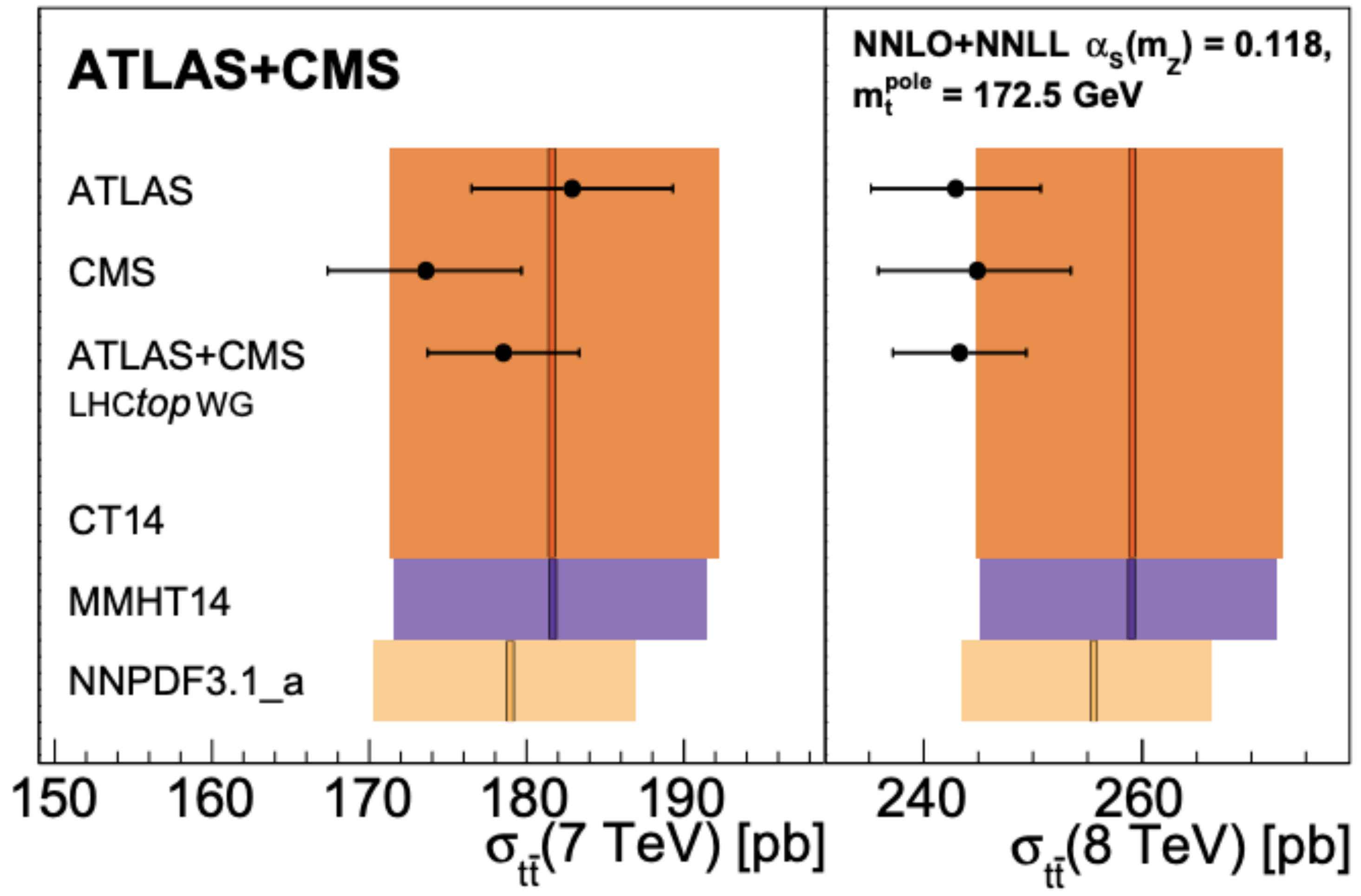
single top production



Top pair cross section measurements

ATLAS+CMS combination 7/8 TeV

- Inputs: e-μ channel with best precision



- This yields a ~25% reduction of uncertainties

$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\,\text{TeV}\ ) \quad = \quad 178.5 \pm 4.7\ \text{pb}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\,\text{TeV}\ ) \quad = \quad 243.3^{+6.0}_{-5.9}\ \text{pb}.$$

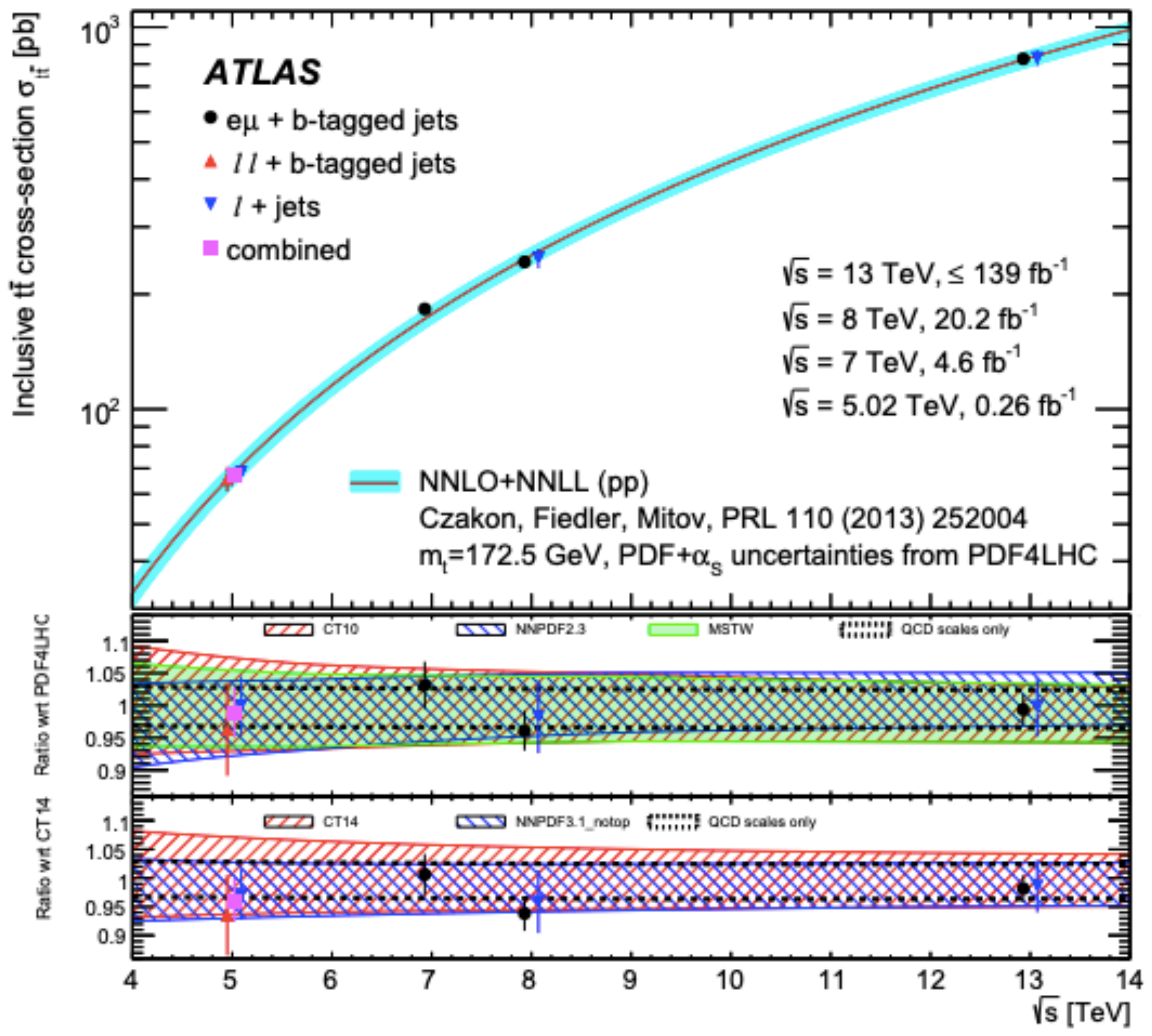
- The results are used for an accurate determination of

$$\alpha_s(m_Z) = 0.1170^{+0.0021}_{-0.0018} \qquad m_t^{\text{pole}} = 173.4^{+1.8}_{-2.0}\ \text{GeV}$$

arXiv:2205.13830

Measurements at 5.02 TeV

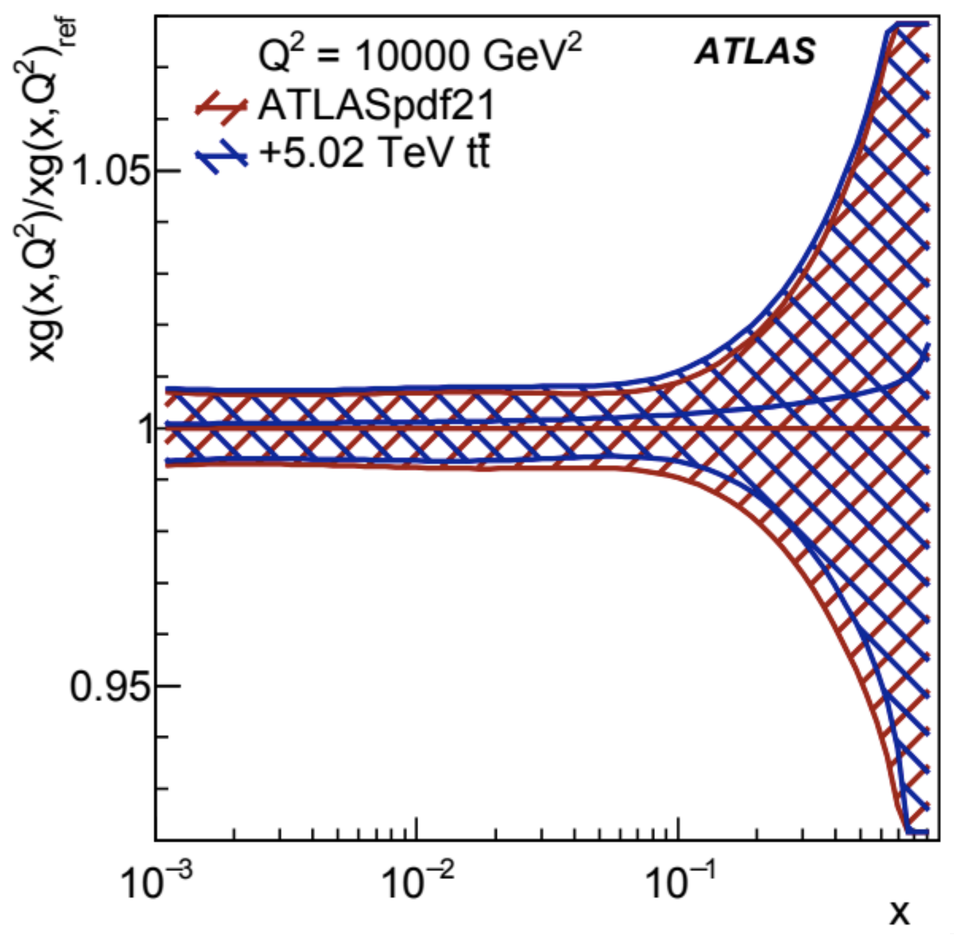
arXiv:2207.01354



Impressive agreement with the QCD prediction over pp collision energies from 5 to 13 TeV and an order of magnitude of cross-section

$\sigma_{t\bar{t}}(\sqrt{s})$ helps also to constrain PDFs

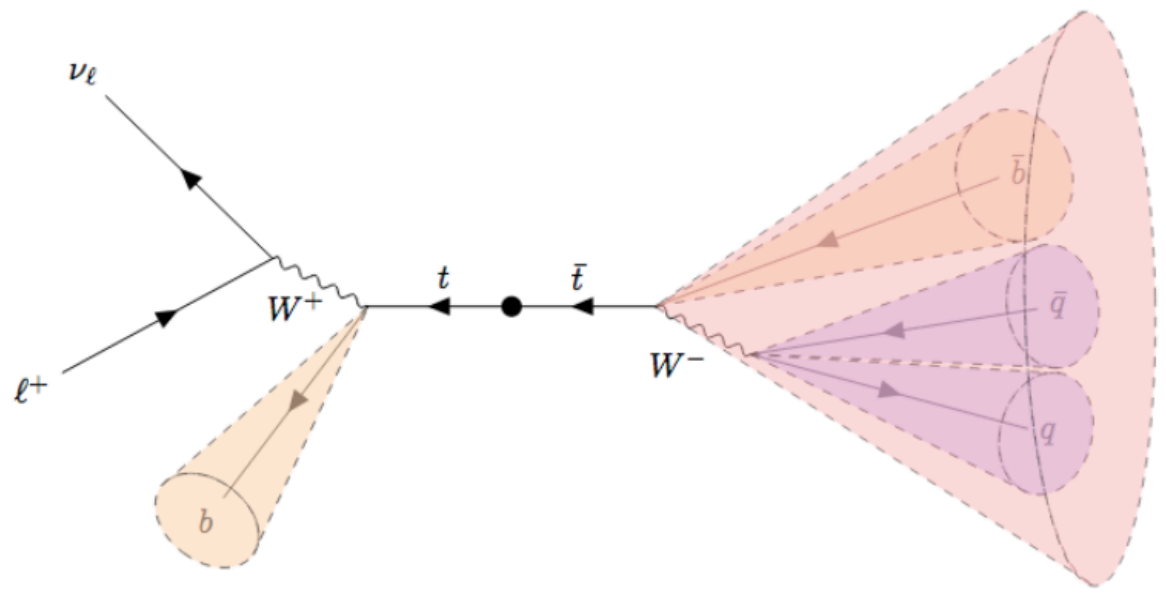
The 5 TeV ATLAS result reduces the uncertainty on xg(x) by 5% at x=0.1



Measurements in boosted topology

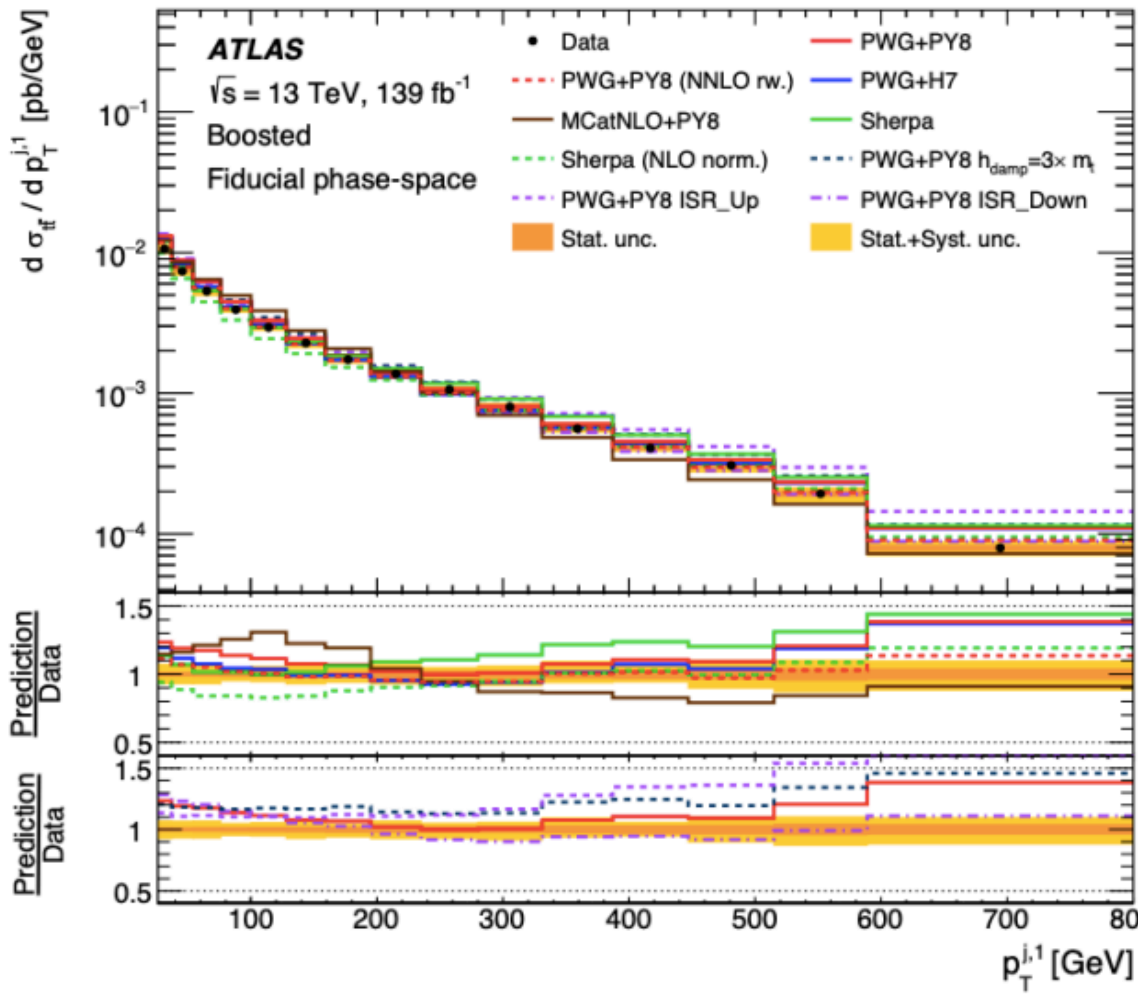
Single lepton channel

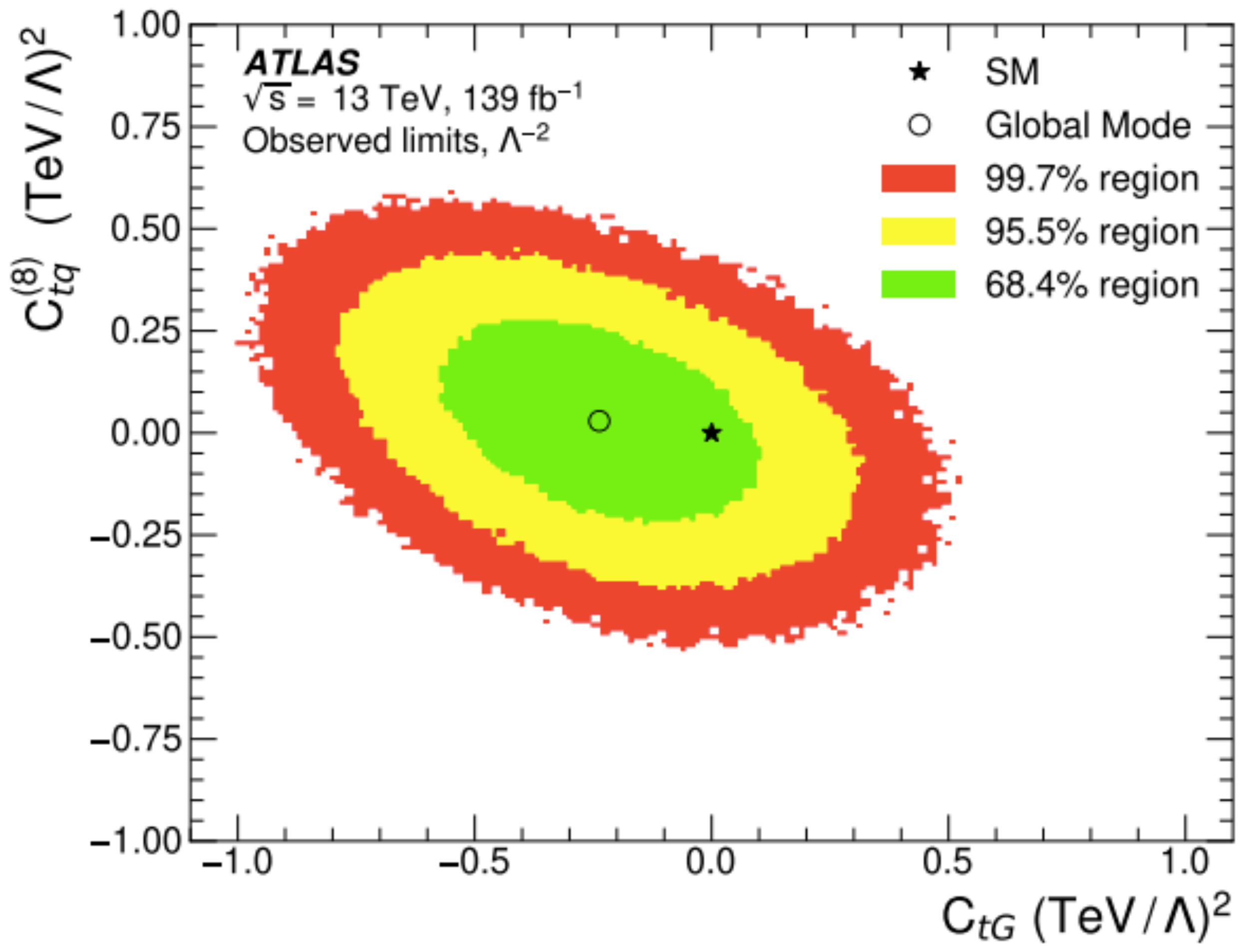
Select l + b-jet + top-tagged wide jet



Significant reduction of JES uncertainty due to in-situ JES calibration

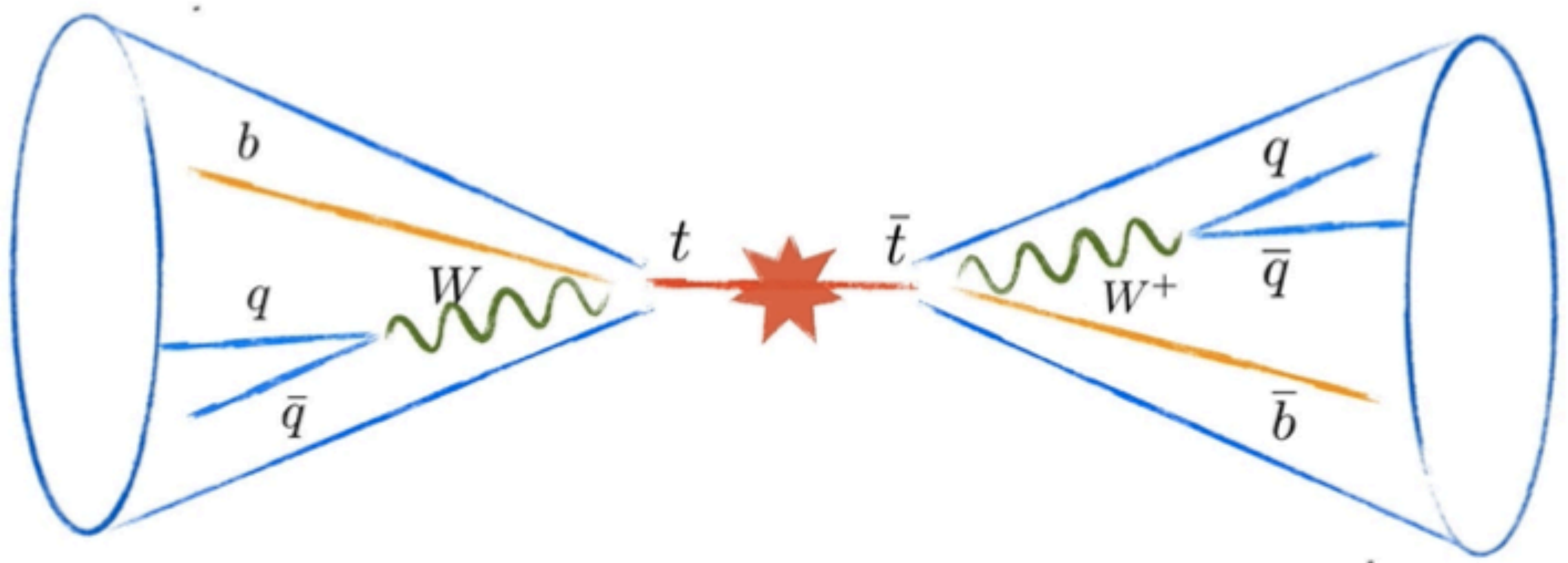
Aditional jet pT's are generally not well described by QCD models

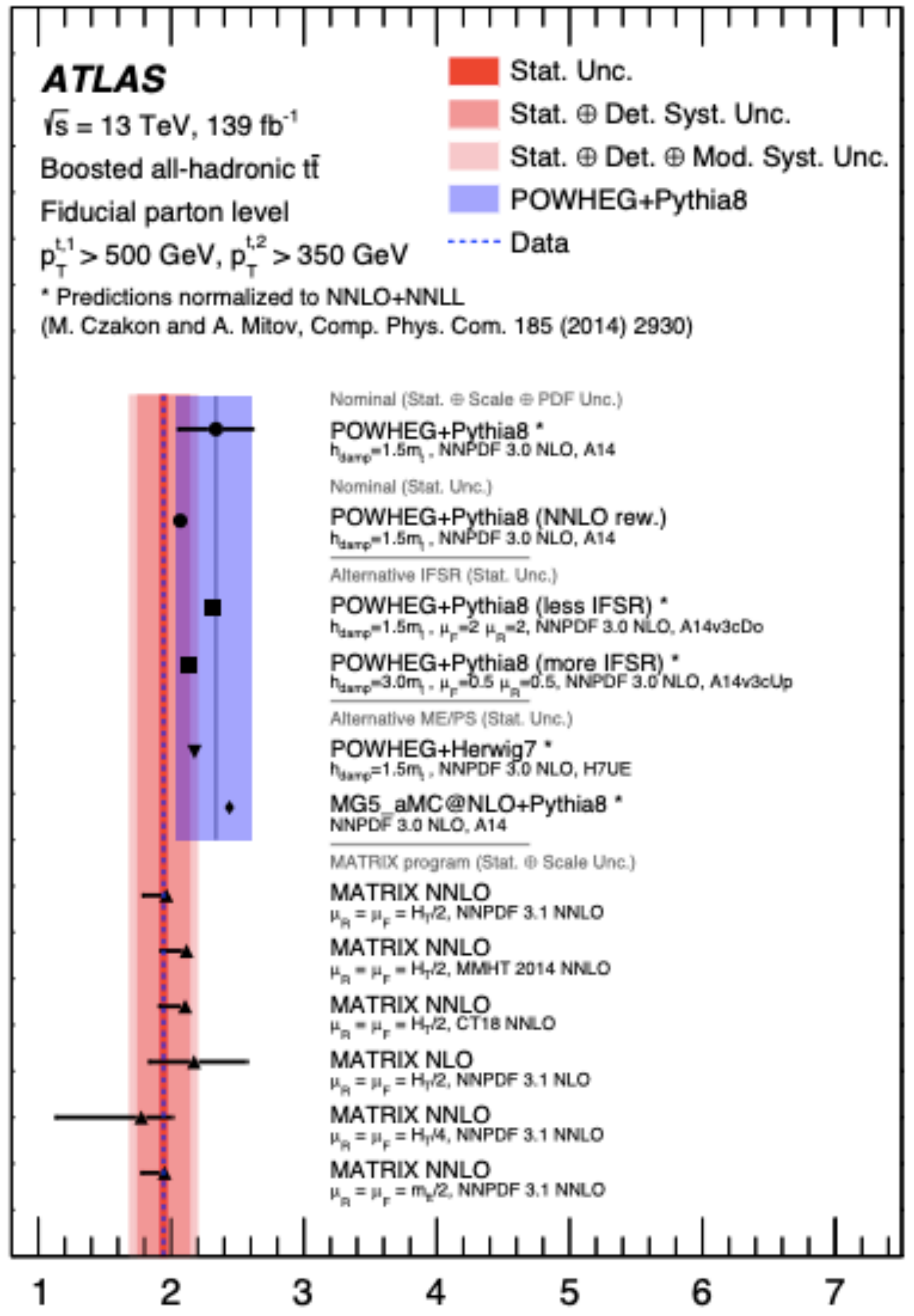




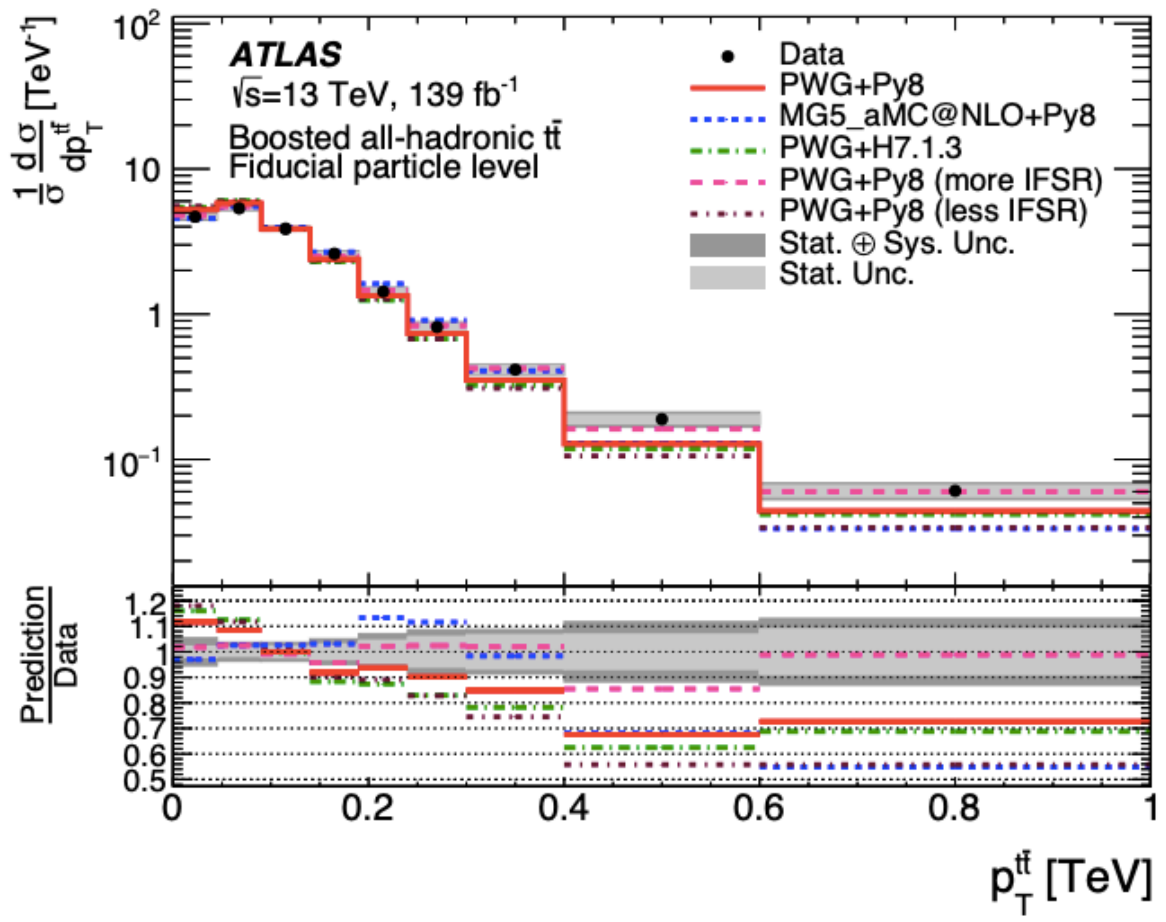
Limits are set on the Wilson coefficients of the dimension-six operators

All-hadronic channel





- MATRIX reproduces the fiducial cross-section better than the NLO models



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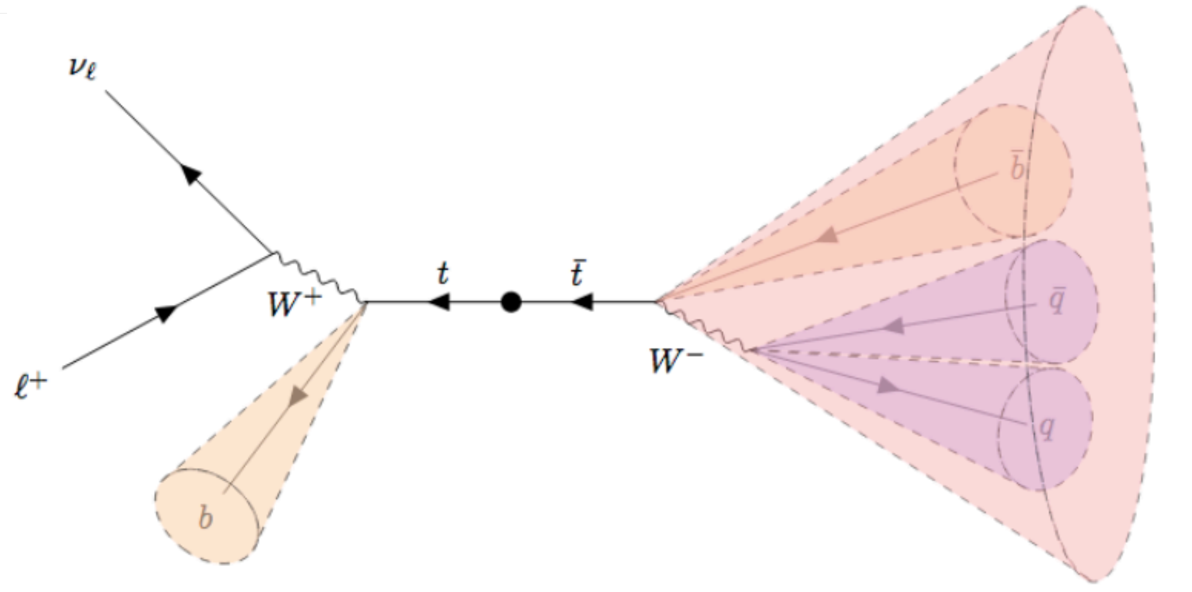

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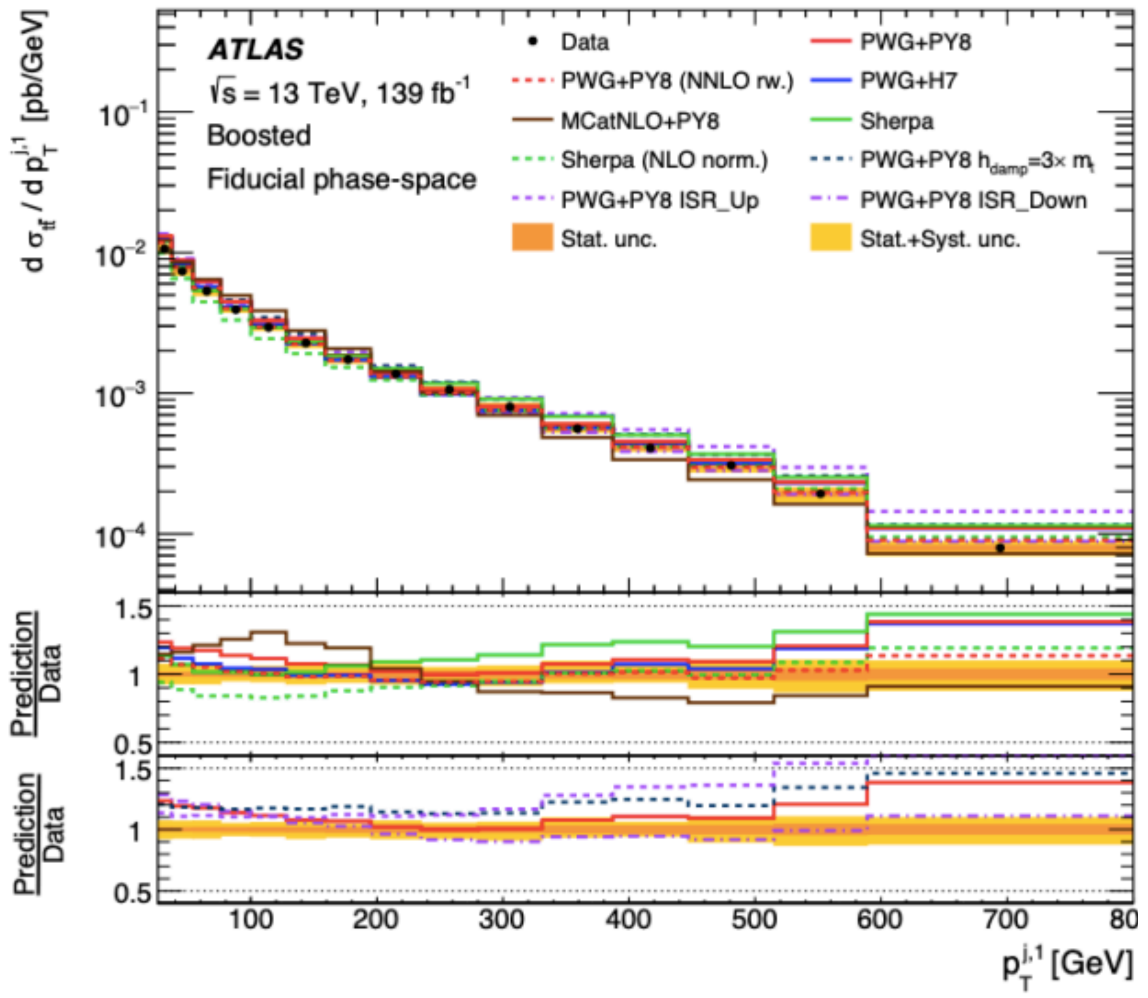

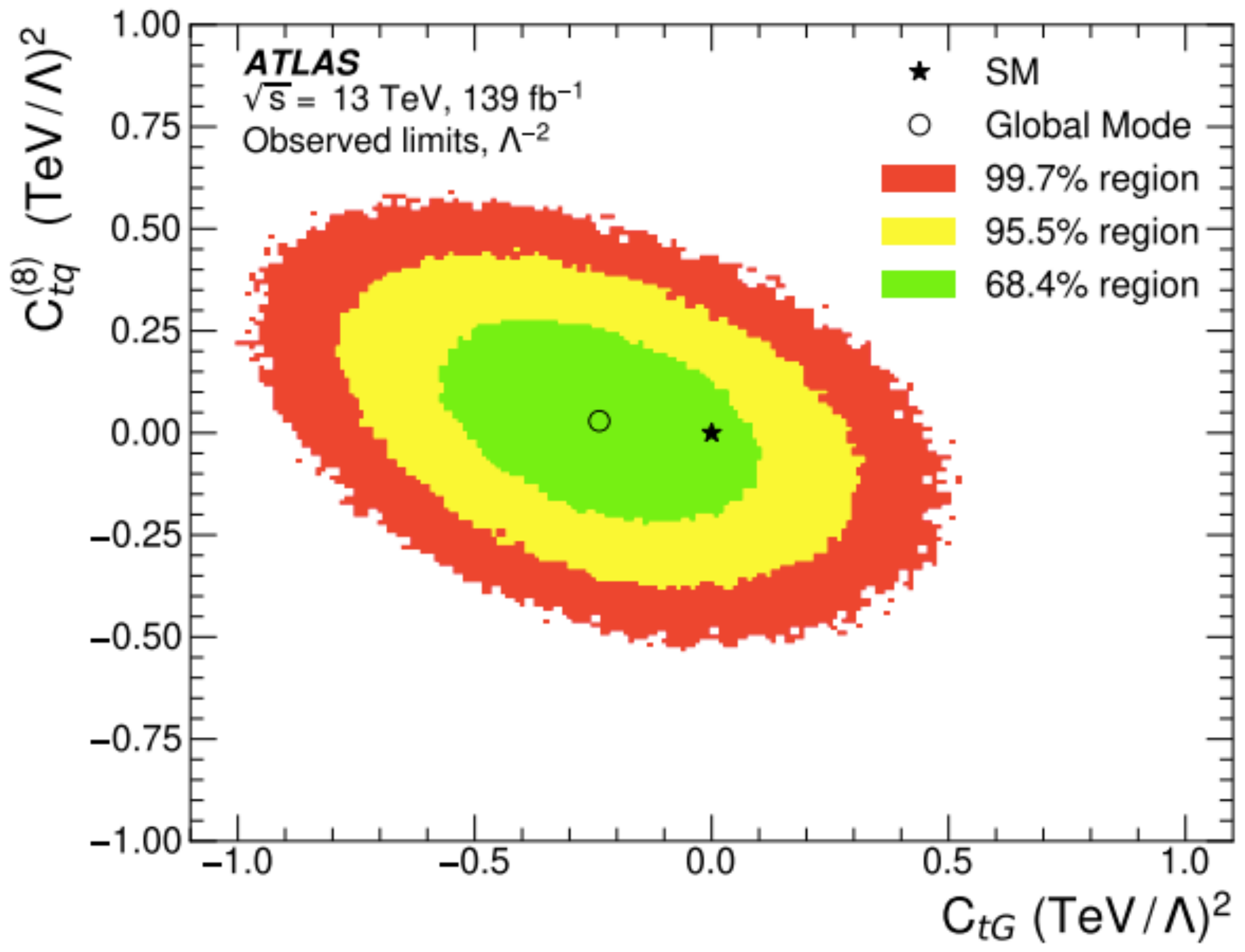

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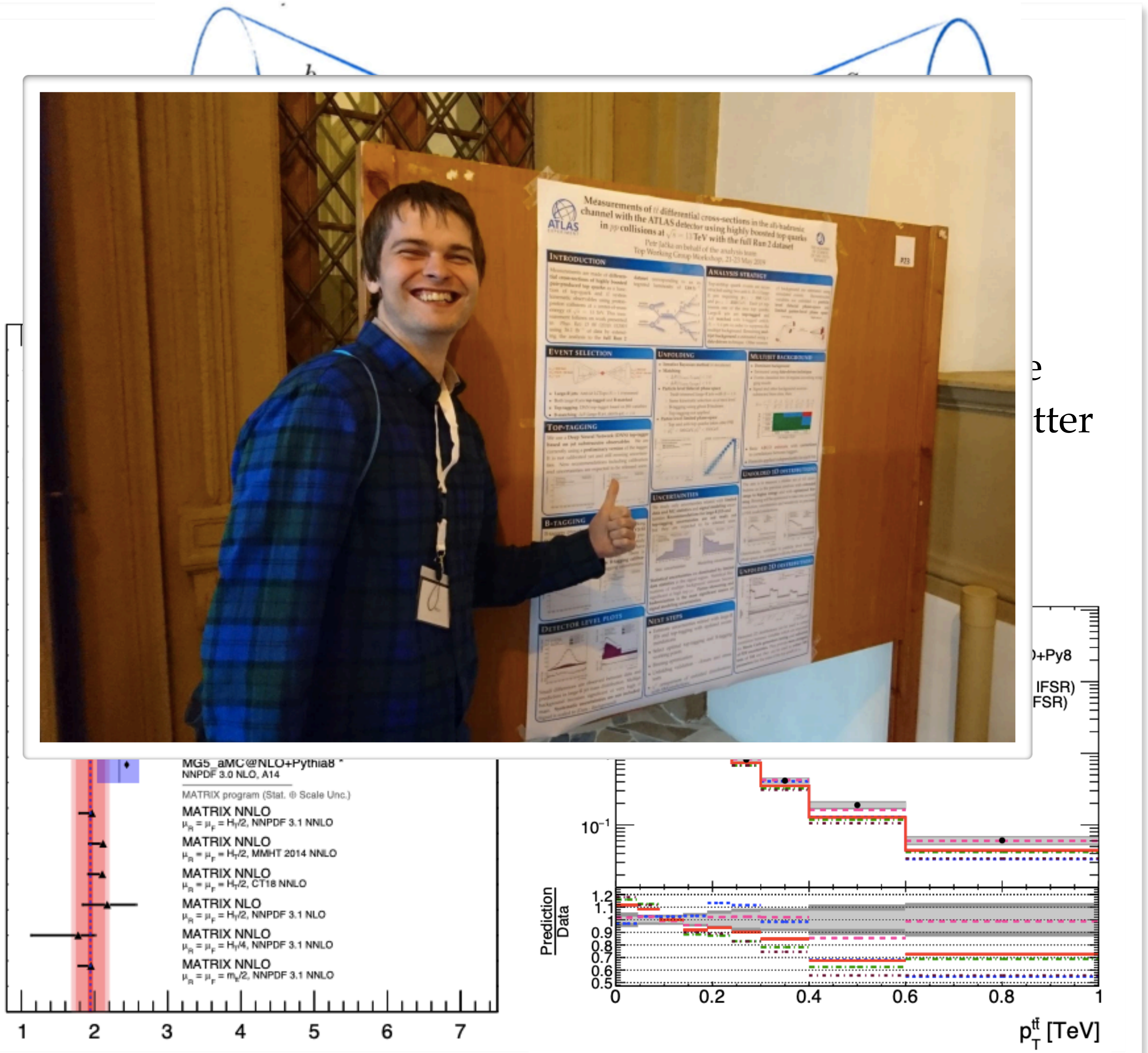
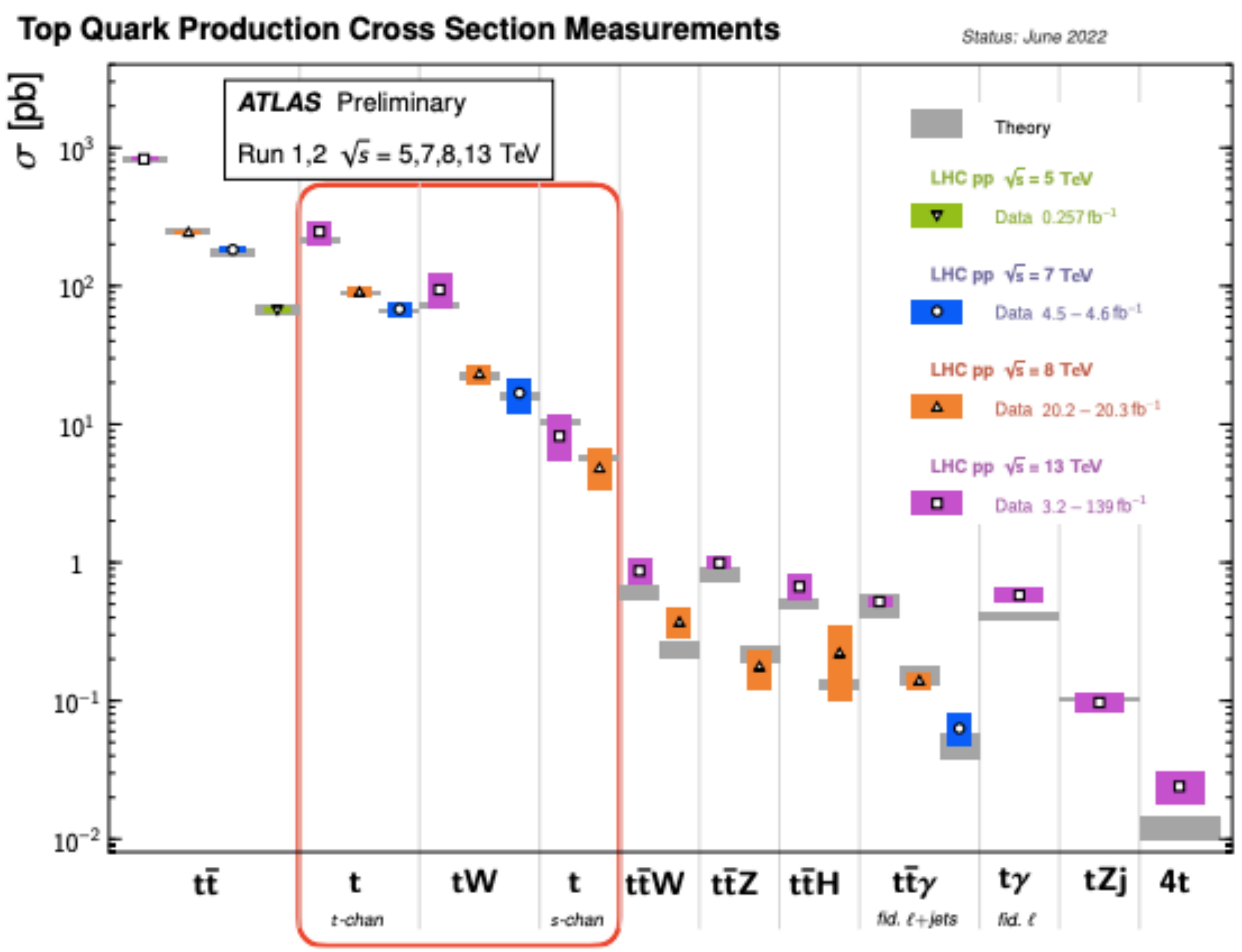
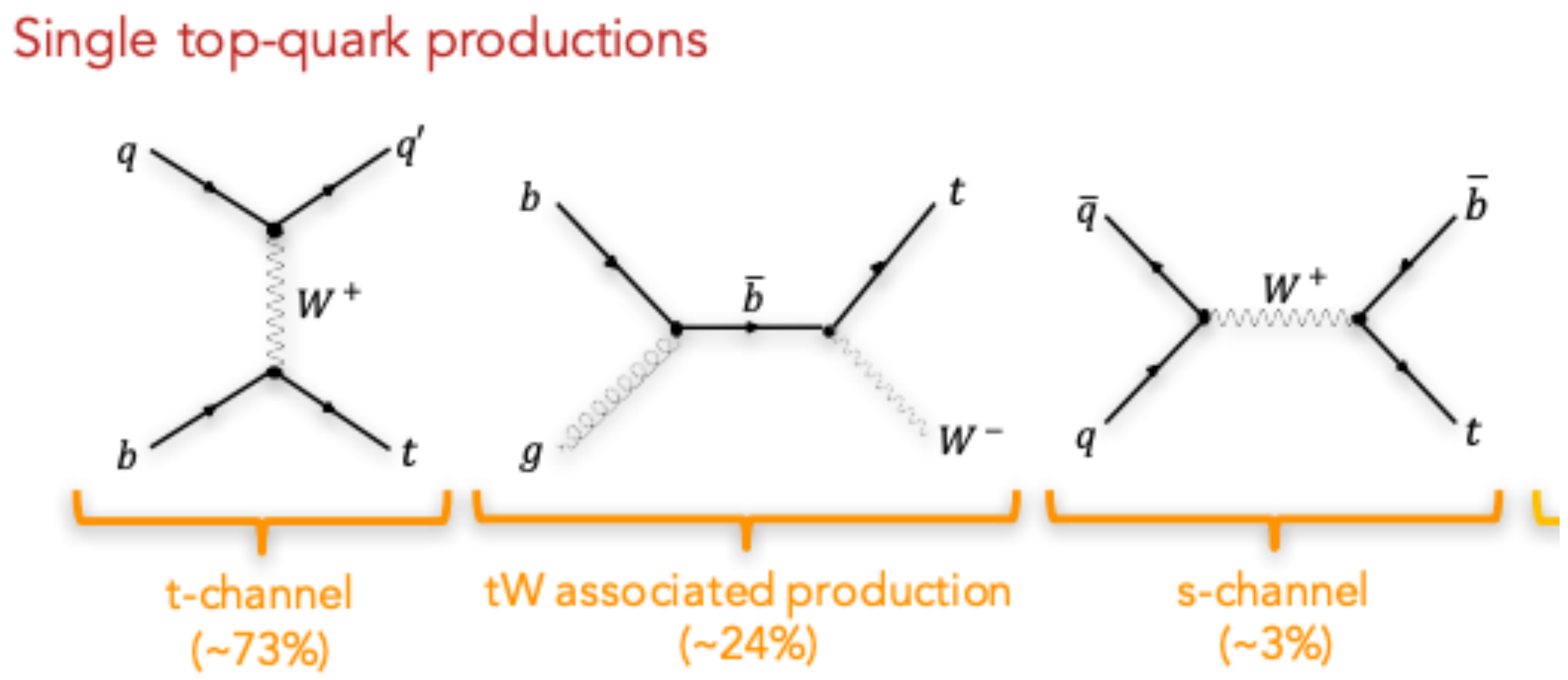
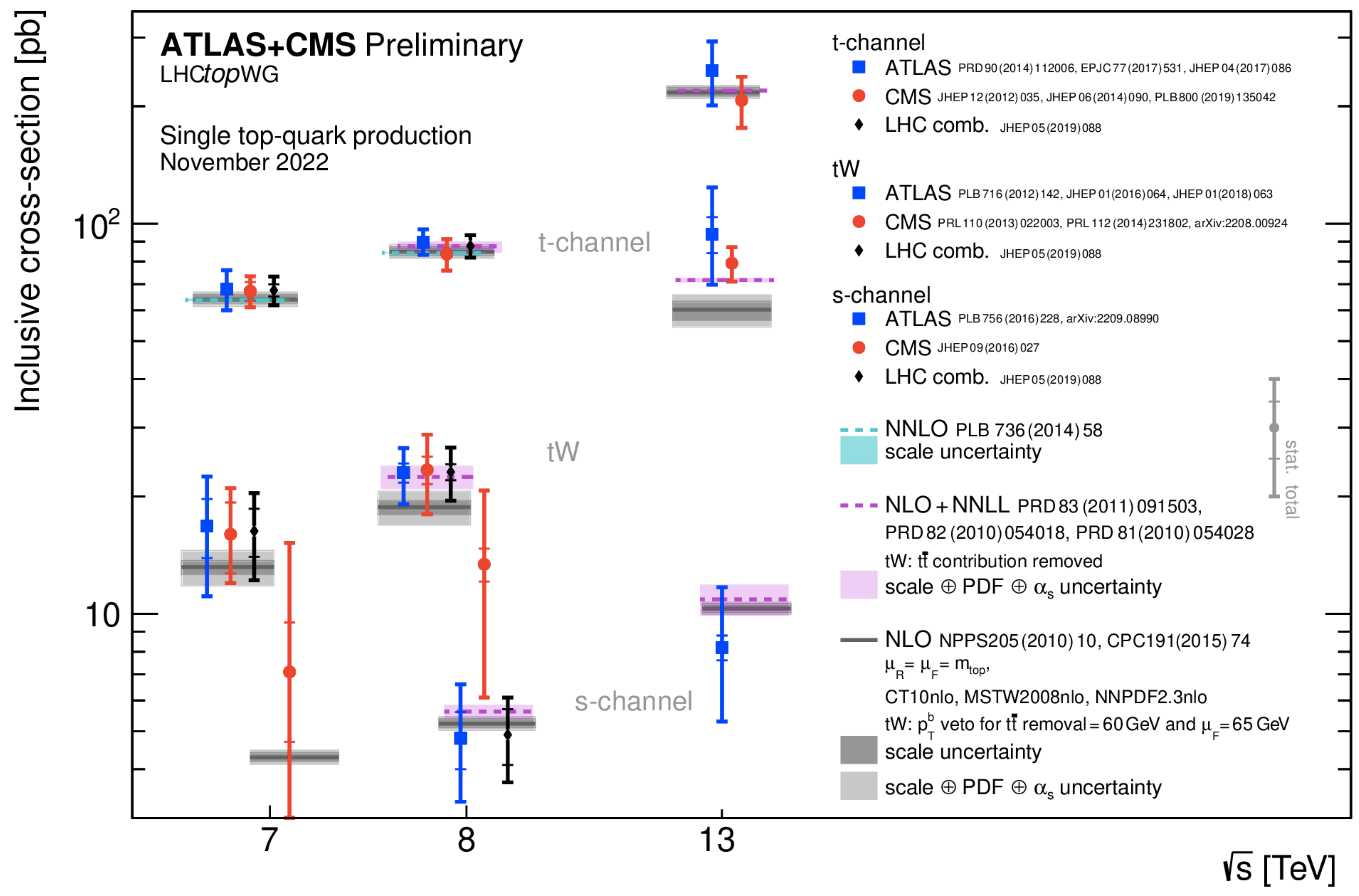


Single top production







$$\sigma_{\mathrm{t\ ch.}}(13\ \mathrm{TeV}) = 217.0^{+6.6}_{-4.6}(\mathrm{scale}) \pm 6.2(\mathrm{PDF}, \alpha_S)\ \mathrm{pb}$$

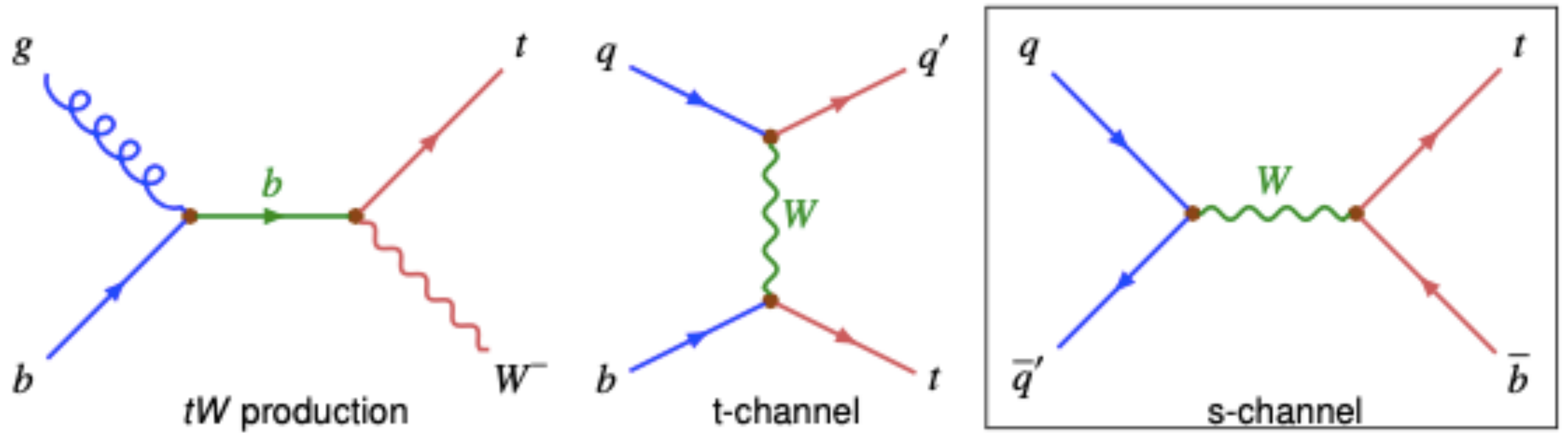
$$\sigma_{\mathrm{s\ ch.}}(13\ \mathrm{TeV}) = 10.32^{+0.29}_{-0.24}(\mathrm{scale}) \pm 0.27(\mathrm{PDF}, \alpha_S)\ \mathrm{pb}$$

$$\sigma_{\mathrm{tW\ ch.}}(13\ \mathrm{TeV}) = 71.7 \pm 1.8(\mathrm{scale}) \pm 3.4(\mathrm{PDF}, \alpha_S)\ \mathrm{pb}$$

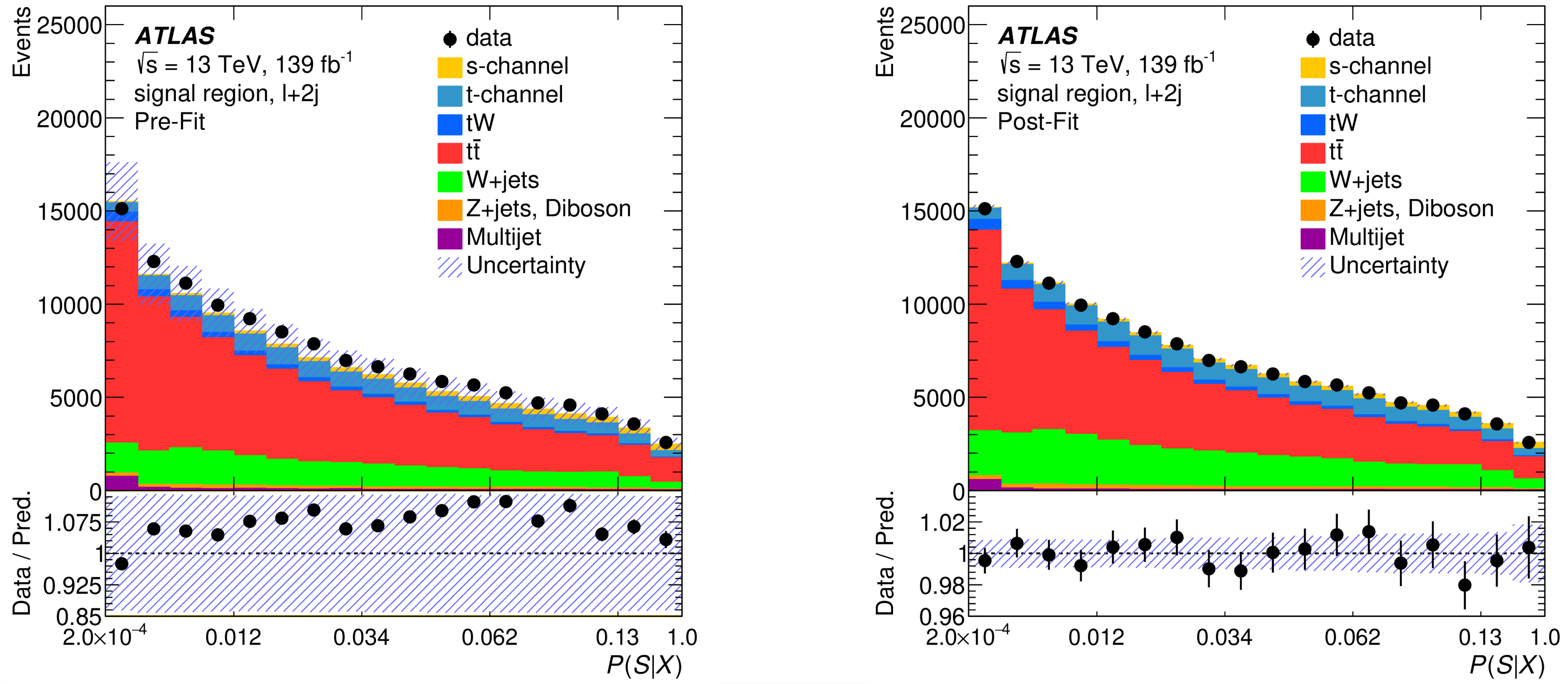
Single top s-channel at 13 TeV

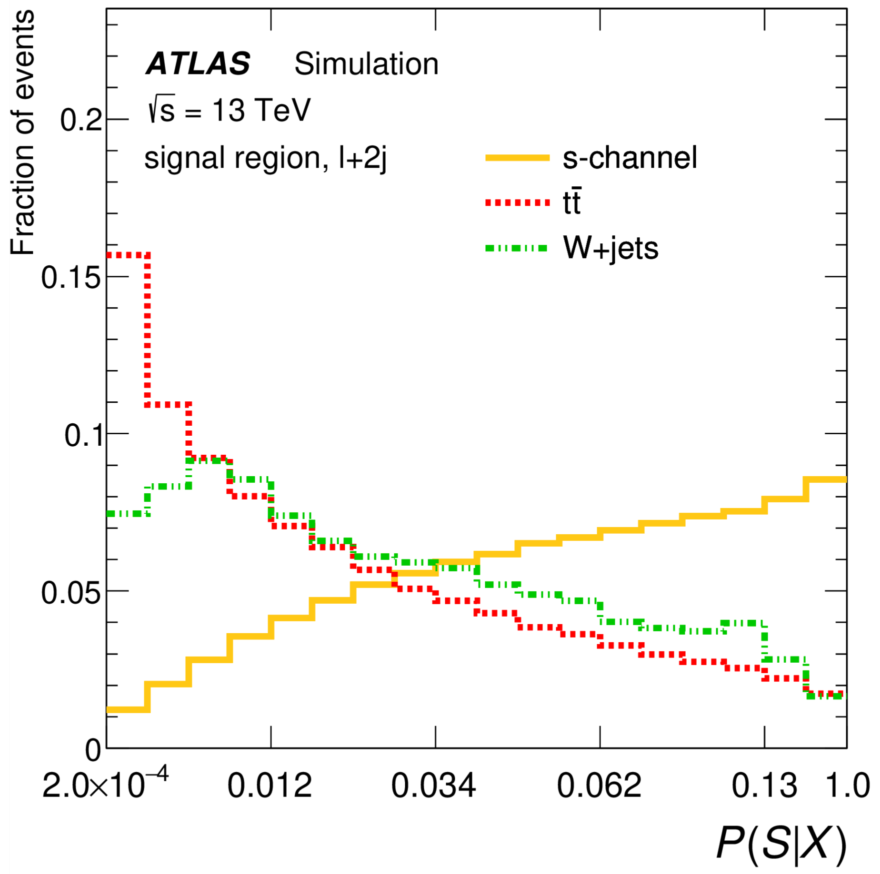
arXiv:2209.08990
submitted to JHEP

- Observed at Tevaton combining D0 and CDF
- s-channel : the most challenging at the LHC
  - not yet observed in pp collisions



Distribution of the MEM discriminant in the SR before and after the fit





- Matrix Element Method (for Signal and Bkg separation)
- P(S | X): probability for a measured event X to be a signal event S

- Measurements dominated by modelling and JES

Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ normalisation	$+24/-17$
Jet energy resolution	$+18/-12$
Jet energy scale	$+18/-13$
Other s-channel modelling sources	$+18/-8$

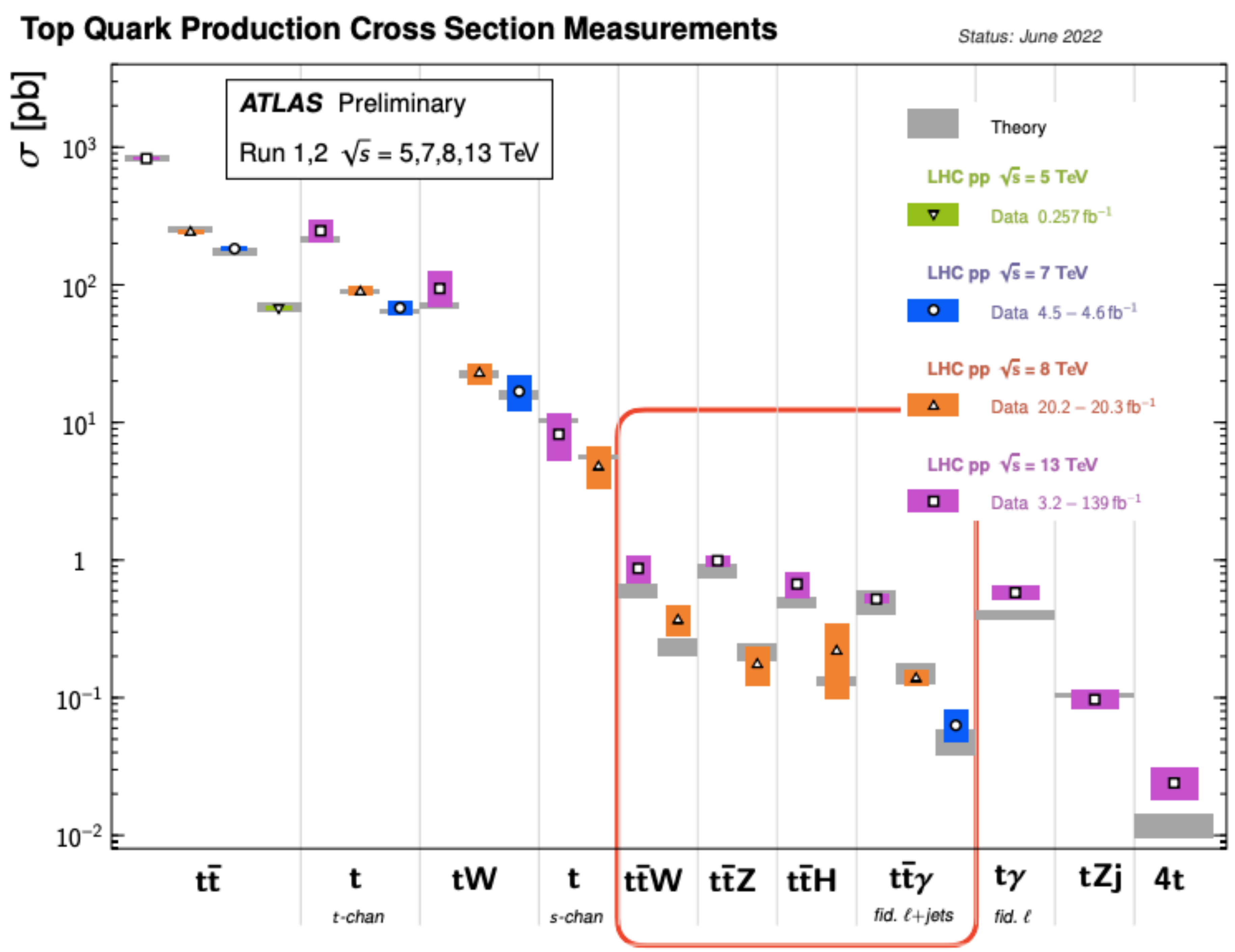
- Measured cross-section :

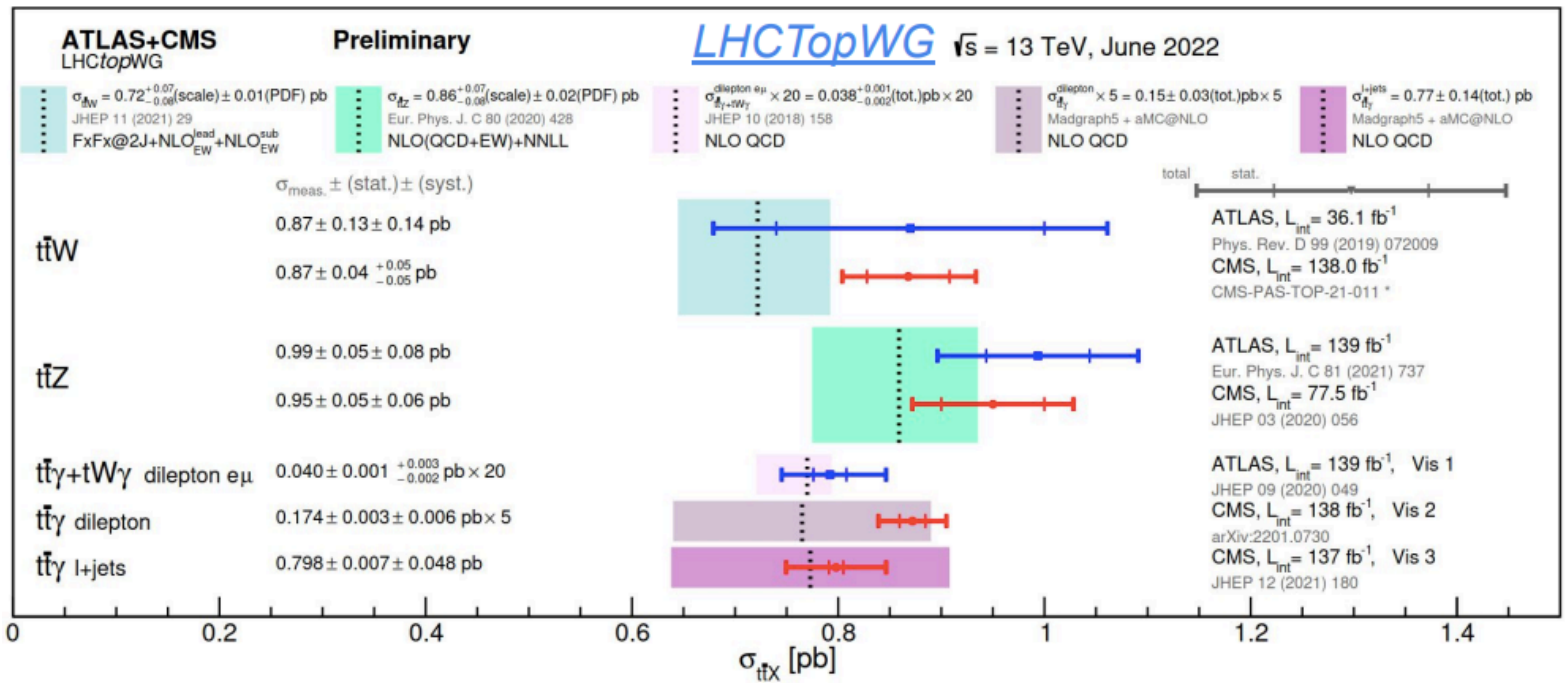
$$\sigma_{\rm obs} = 8.2^{+3.5}_{-2.9}\ \text{pb}$$

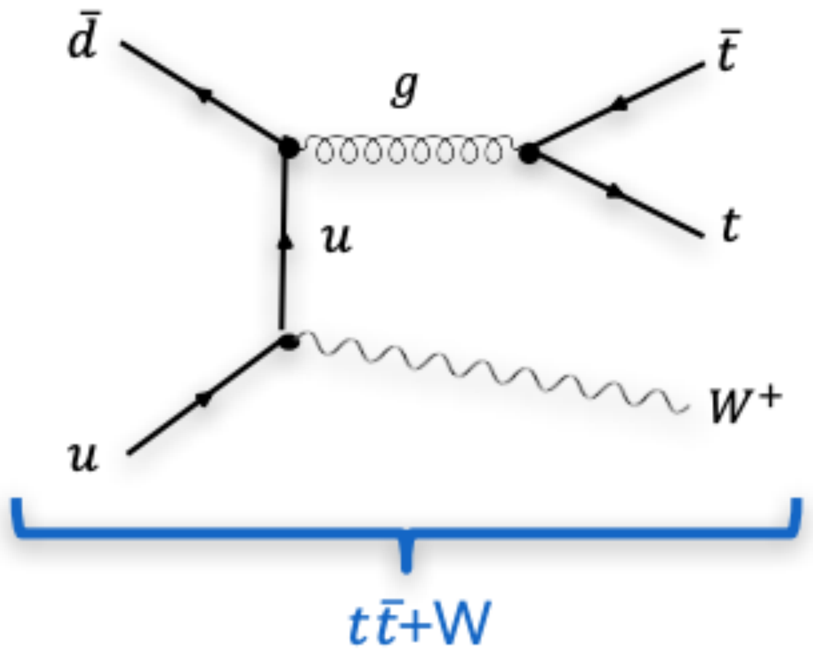
$$\sigma_{\rm SM} = 10.32^{+0.40}_{-0.36}\ \text{pb}$$

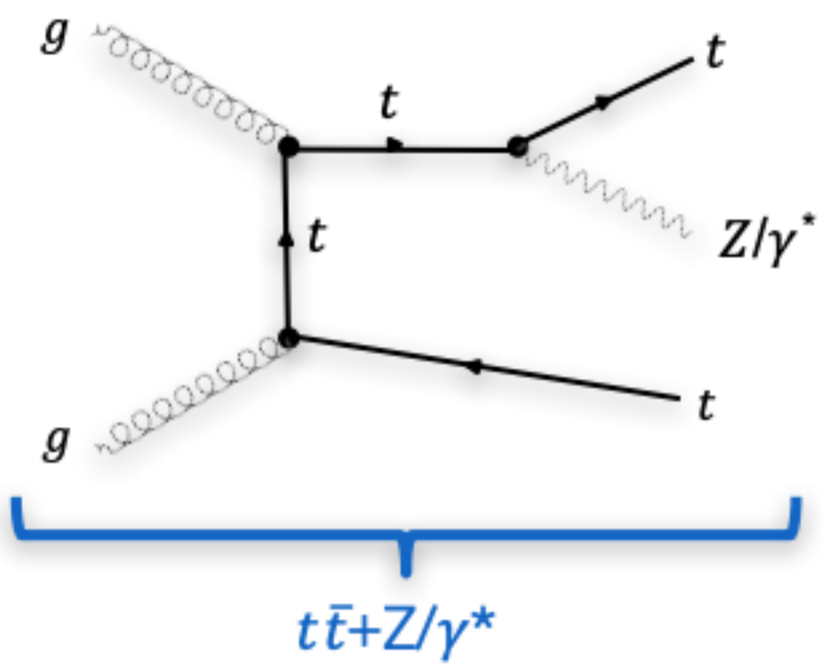
} 3.3 σ (3.9 σ) observed (expected) significance

tt+X production









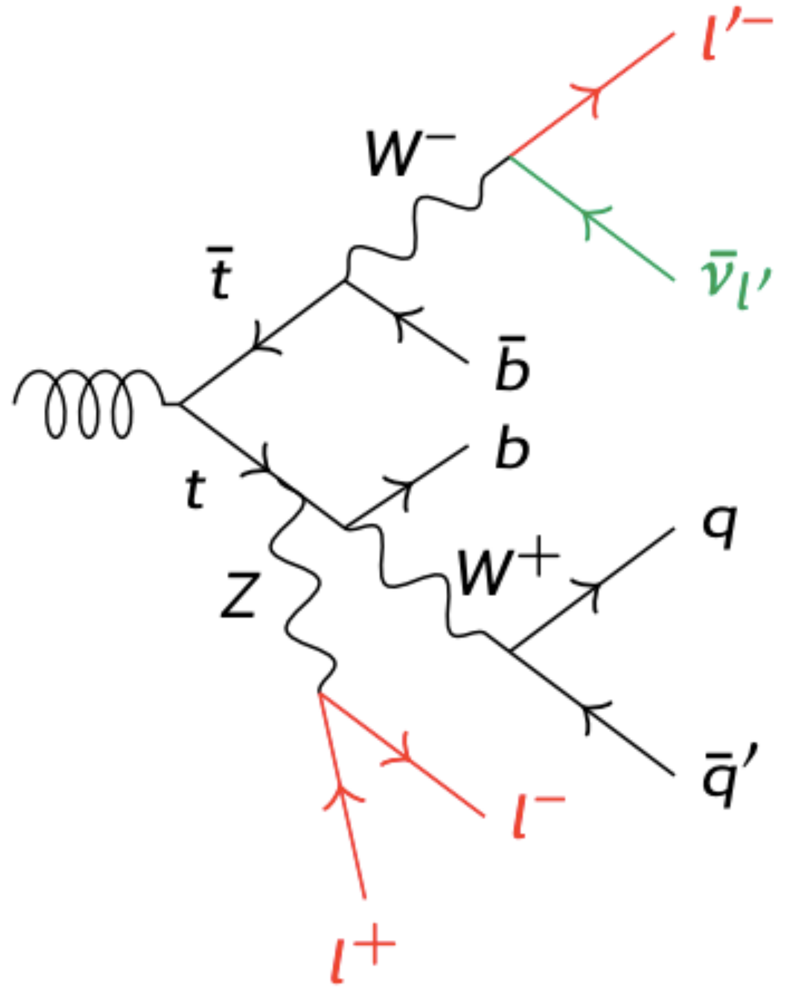
- High precision inclusive/differential measurements of tt+γ/Z/W
  - High purities in lepton-dominated final states
  - Most lepton channels covered by ATLAS+CMS in Run 2

ttZ production

EPCJ 81 (2021) 737

- Measurement of ttZ in multilepton channels
- Fit in lepton / jet / b-jet bins

Channel	$\mu_{t\bar{t}Z}$
Trilepton	$1.17 \pm 0.07\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$
Tetralepton	$1.21 \pm 0.15\,(\text{stat.})\,^{+0.11}_{-0.10}\,(\text{syst.})$
Combination ($3\ell + 4\ell$)	$1.19 \pm 0.06\,(\text{stat.})\, \pm 0.10\,(\text{syst.})$



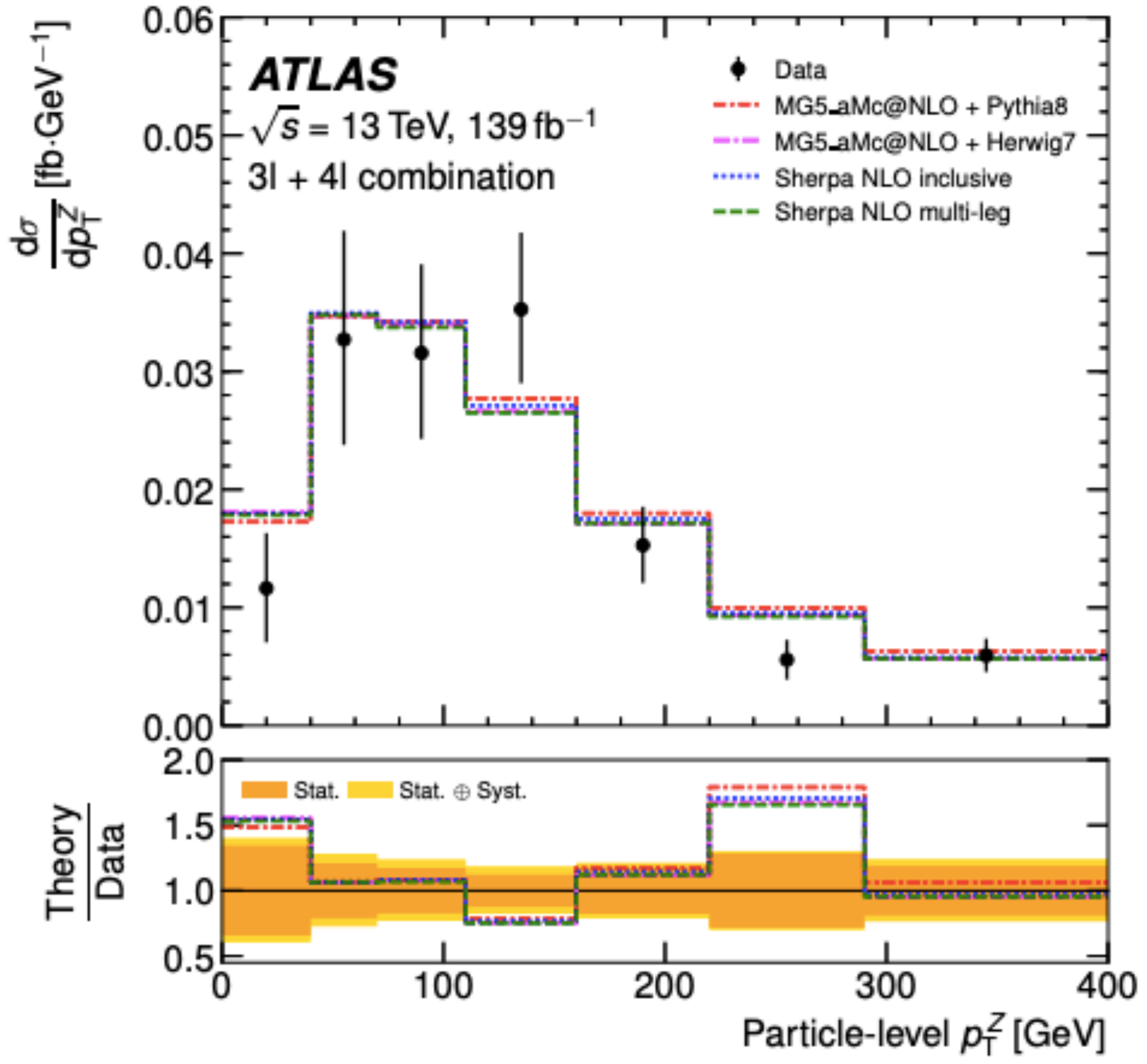
- Measured cross-section :

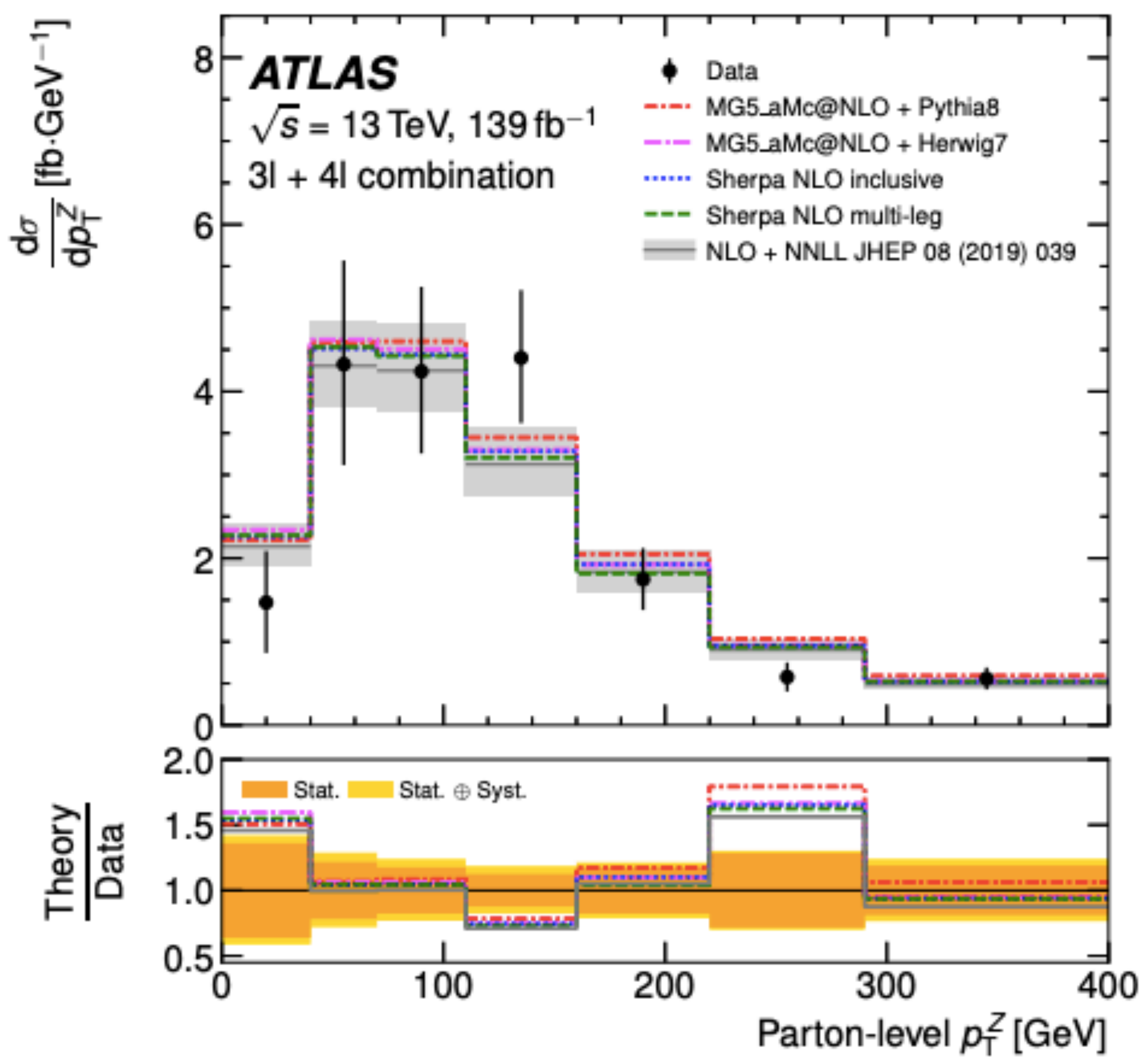
$$\sigma^{t\bar{t}Z}_{obs.} = 0.99 \pm 0.005(stat) \pm 0.08(syst.)\ pb$$

- NLO+NNLL calculation (EPJC 79 (2019) 249):

$$\sigma^{t\bar{t}Z}_{pred.} = 0.86^{+0.07}_{-0.08}(scale) \pm 0.03(pdf + \alpha_S)\ pb$$

- Dominated by PS modeling, backgrounds, b-tagging



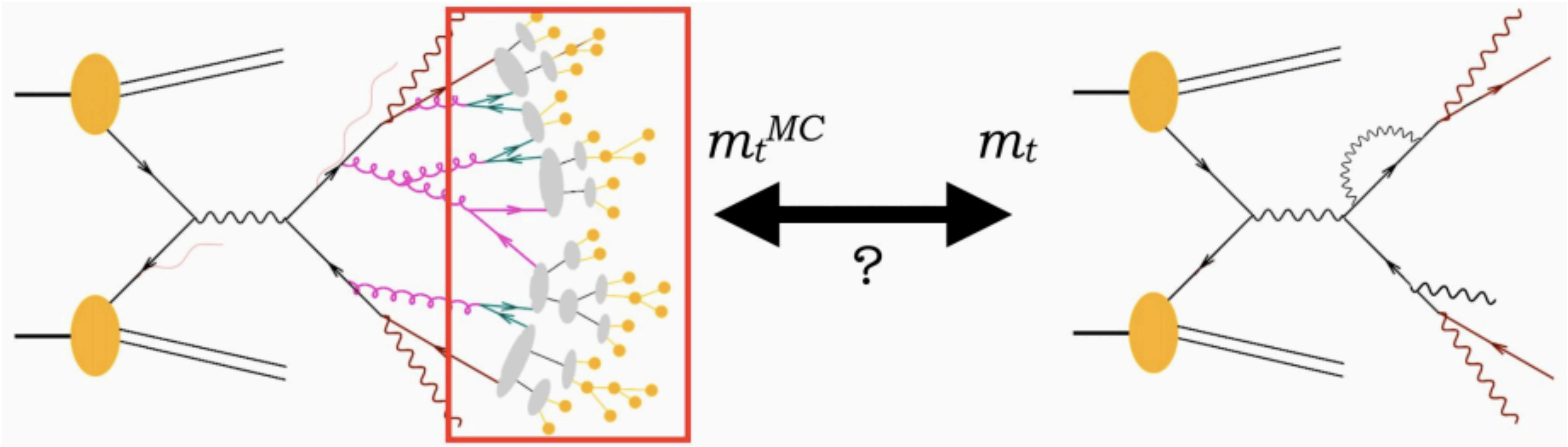


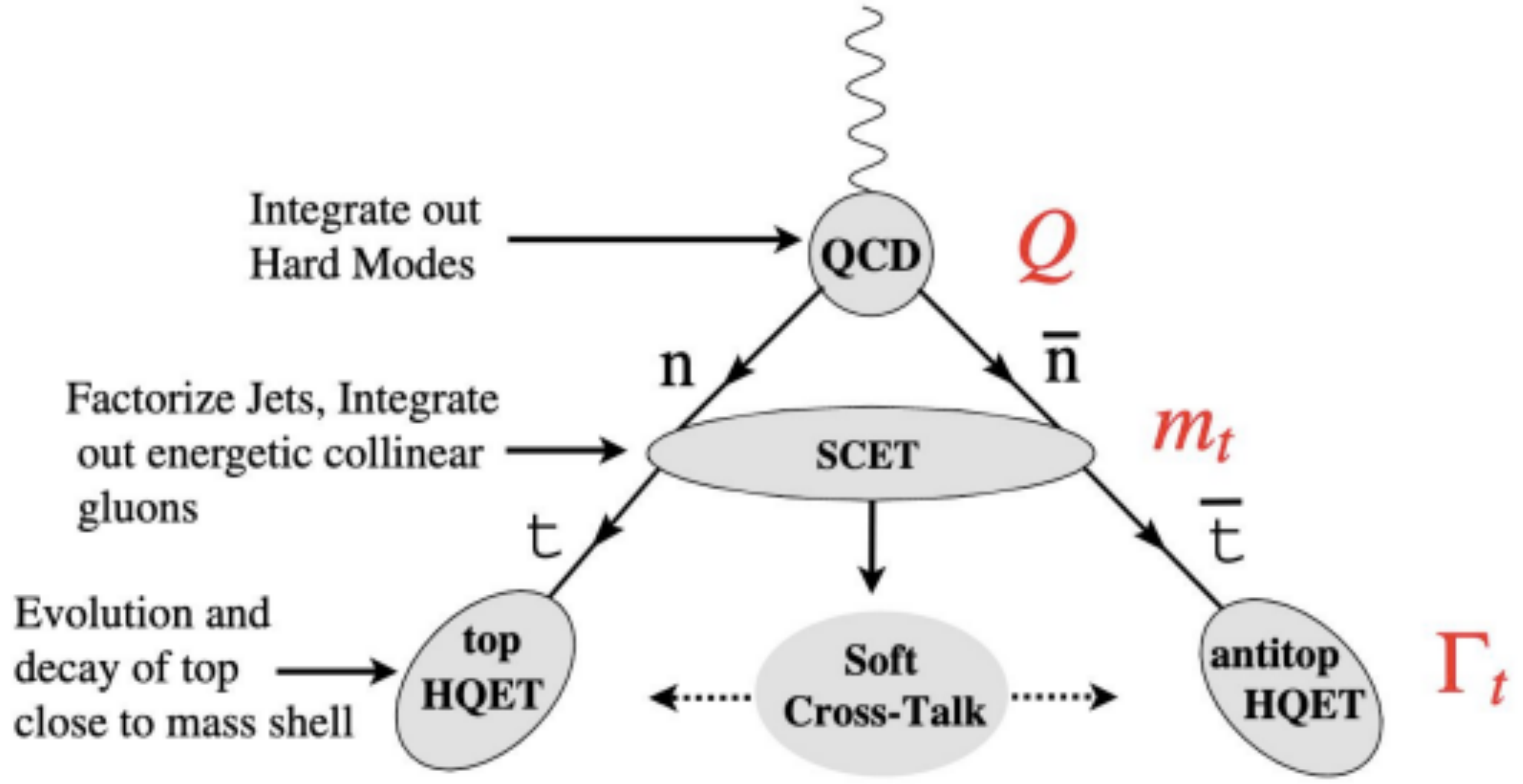
- Differential measurement (parton and particle level)
  - Various observables in 3ℓ and 4ℓ channel
- Compared to multiple simulations and NLO+NNLL calculation (JHEP 08, 039 (2019))

➢ (Similar trends for most simulations and calculations)

Top mass measurement

Classes of top quark mass measurements





"Direct" measurements:

- reconstruct invariant mass of top quark decay products
  - Can be very precise (~0.3 GeV)
  - Depends on the details of the MC simulation

"Indirect" measurements:

- Measure observable directly sensitive to m_t (e.g. inclusive/differential σ^{tt})
- Compare to theory prediction in well-defined renormalisation scheme

"Third way":

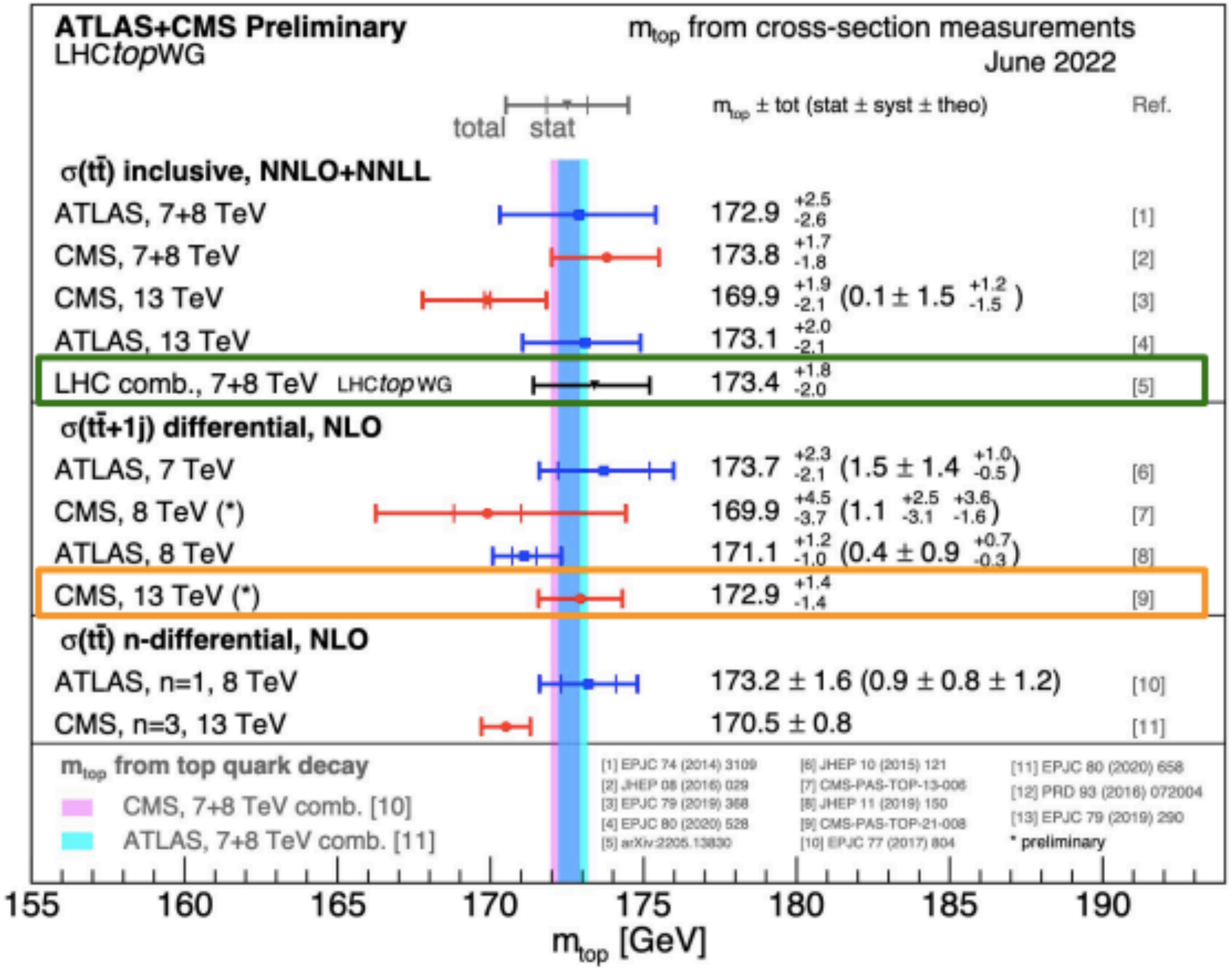
- jet mass in boosted top decays can be calculated using SC-EFT
- → can provide info on relation between m_t MC and m_t (MSR)

Top quark mass measurement

Top quark mass from cross sections: where do we stand

- New result from combined ATLAS+CMS inclusive σ_{tt} at 7+8 TeV
- New measurement from tt+1jet invariant mass from CMS
- Results obtained with different methods overall in good agreement

- Top mass is known to high precision (~0.3% / 0.5 GeV)



Rare top quark production processes

Run 2 data allow to probe the rarest processes with the lowest cross sections

- Stringent tests of the Standard Model
- Tiny anomalies may appear from new physics and can be explored in EFT

Flavour Changing Neutral Currents (FCNC)

- FCNC processes are forbidden at tree level and highly suppressed at higher order in the Standard Model (SM)

FCNC couplings can be described by an EFT:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}^2} \sum_k C_k O_k$$

Λ_{NP} ... scale of new physics

O_k ... dimension-6 operator

Many results of searches for FCNC and rare SM processes involving top quarks

- tqg
- tqγ
- tqZ
- tqH
- $t\bar{t}t\bar{t}$
- tγ
- single top s-channel
- $t\bar{t}W$ charge asymmetry

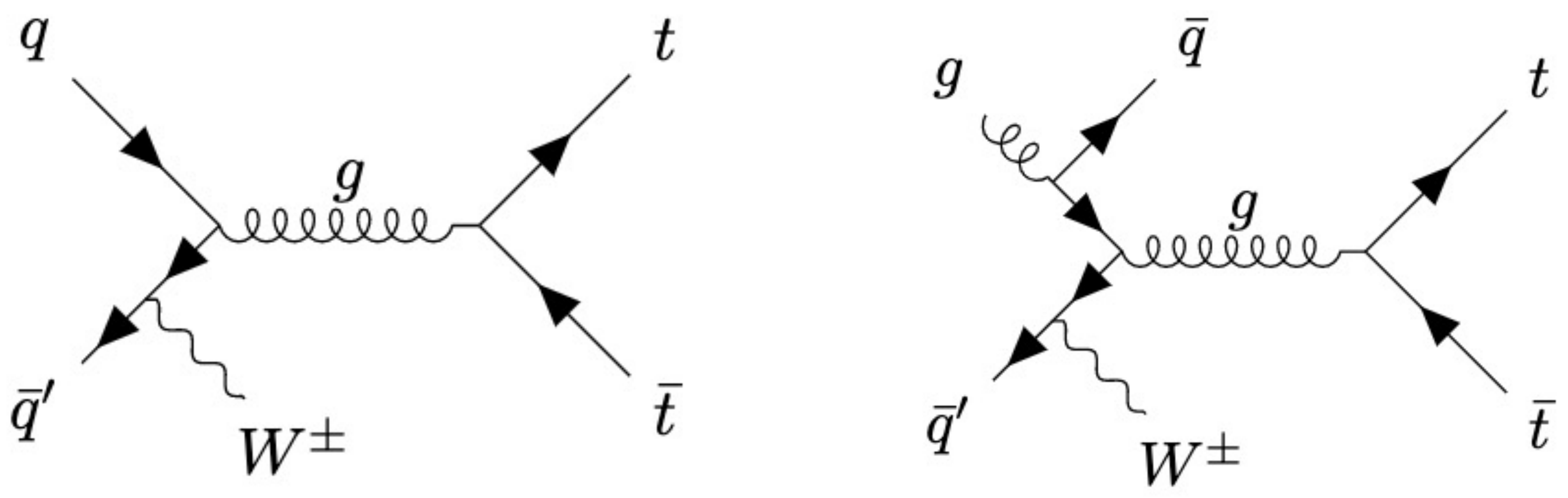
$t\bar{t}W$ leptonic charge asymetry

ATLAS-CONF-2022-062

- First search for the leptonic charge asymmetry of $t\bar{t}W$ in the 3l final state using the full Run2 dataset
- Leptonic Charge Asymmetry:

$$A_C^l = \frac{N(\Delta_\eta^l > 0) - N(\Delta_\eta^l < 0)}{N(\Delta_\eta^l > 0) + N(\Delta_\eta^l < 0)} \text{ , where } \Delta_\eta^l = |\eta_{\bar{l}}| - |\eta_l|$$

- $t\bar{t}W$ process presents larger A_C^l prediction wrt. $t\bar{t}$:
  - $q\bar{q}$ dominated initial state
  - ISR W boson polarizes the top pair
- Lepton-top association is done using a BDT



- Observed A_C^l at reconstruction level:

$$A_C^l\,(t\bar{t}W) = -\,0.123 \pm 0.136(\text{stat.}) \pm 0.051(\text{syst.})$$

Expected: $A_C^l\,(t\bar{t}W)_{SM} = -\,0.084^{+0.005}_{-0.003}\,(\text{scale}) \pm 0.006\,(\text{MC stat.})$

- Unfolding to particle level:

$$A_C^l\,(t\bar{t}W)^{PL} = -\,0.112 \pm 0.170\,(\text{stat.}) \pm 0.055\,(\text{syst.})$$

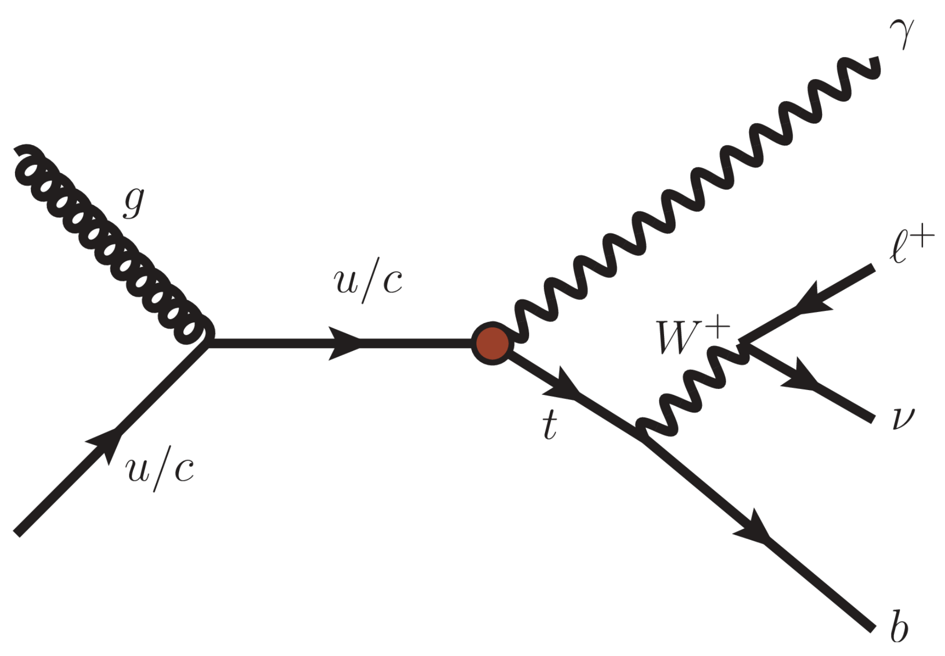
Expected: $A_C^l\,(t\bar{t}W)^{PL}_{SM} = -\,0.063^{+0.007}_{-0.004}\,(\text{scale}) \pm 0.004\,(\text{MC stat.})$

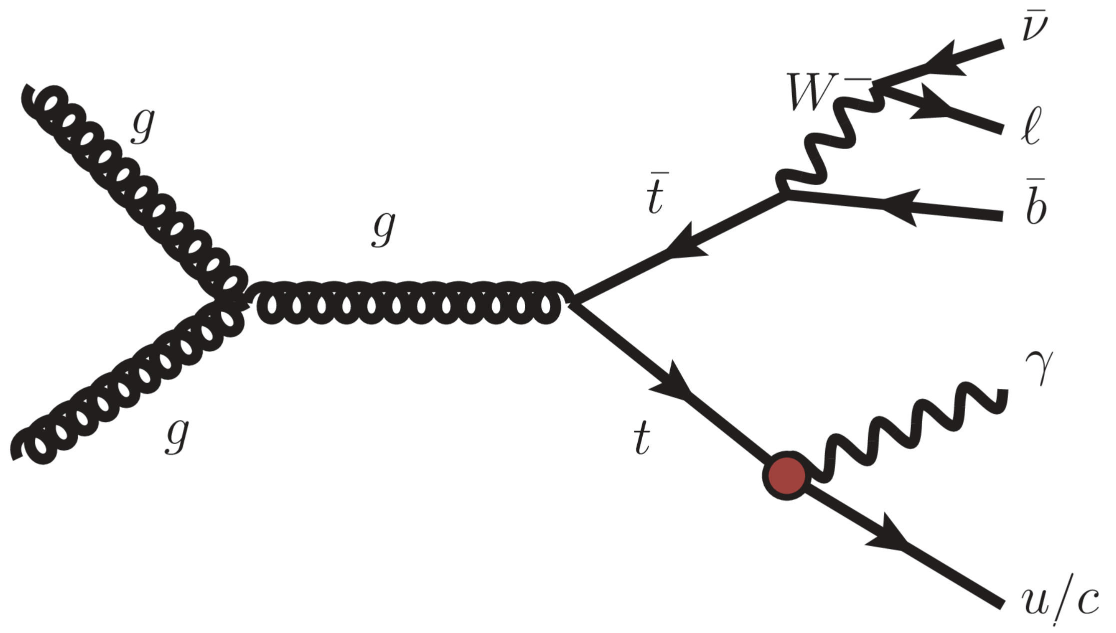
- Analysis is dominated by statistical uncertainties

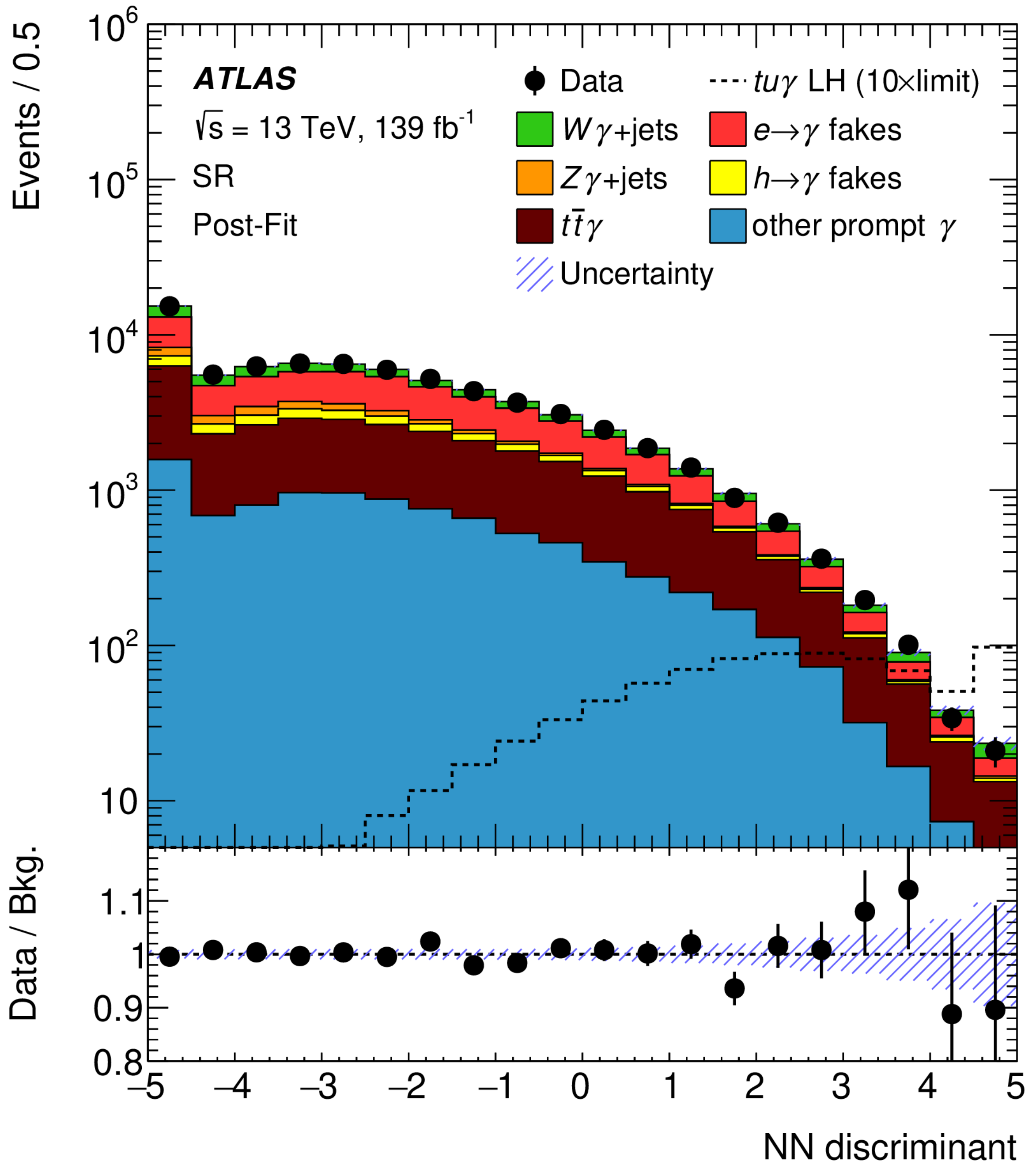
FCNC tqγ

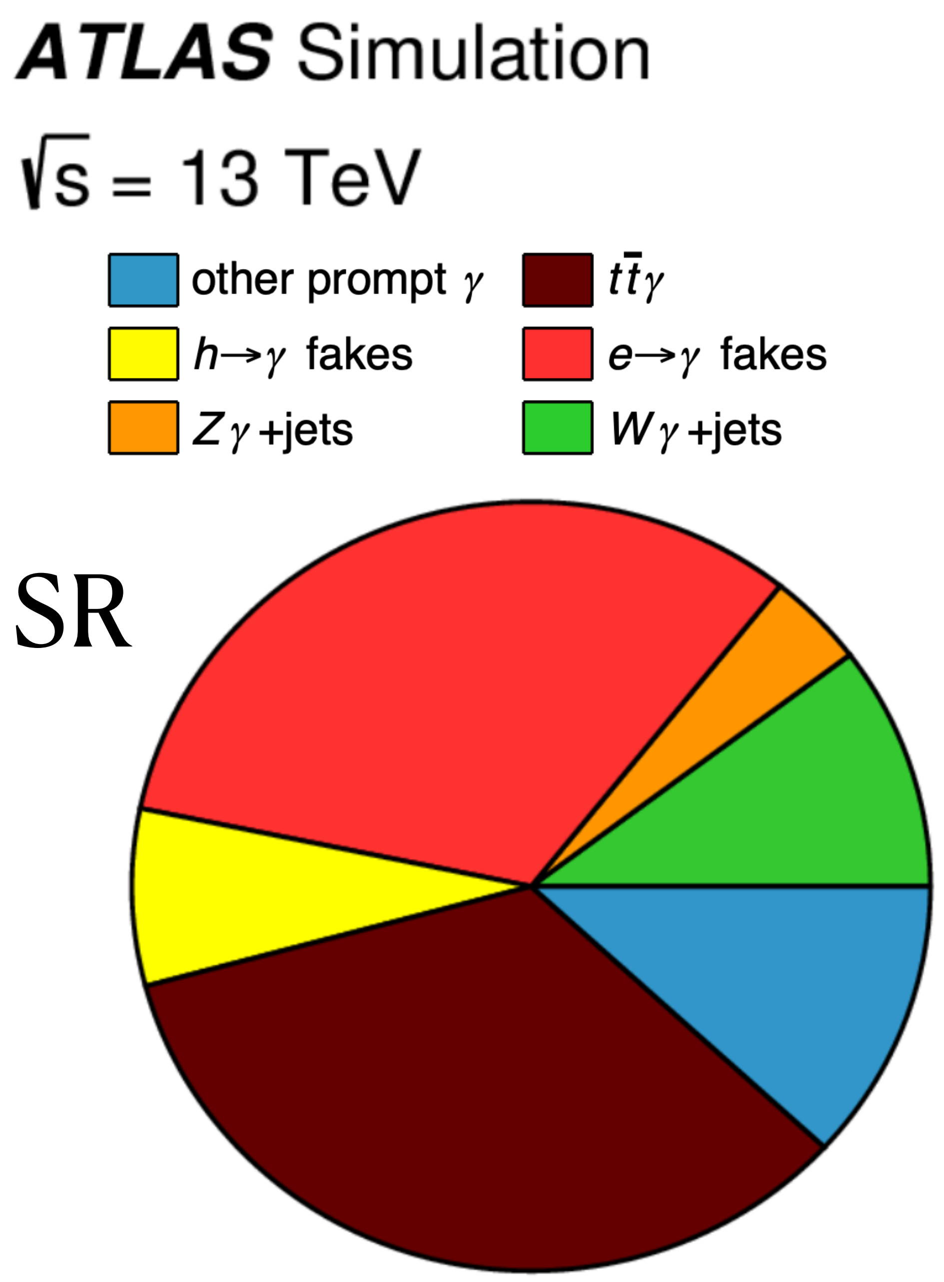
arXiv:2205.02537
submitted to Phys. Lett. B

- Target both production and decay of FCNC tγq vertices
- Background estimation
  - e→γ: estimate a fake factor to correct simulation
  - h→γ: transfer factor from control region
- Two neural network targeting tuγ and tcγ signal separately









- Upper limits of BR

Effective coupling	Coefficient limits		Coupling	BRs $[10^{-5}]$	
	Expected	Observed		Expected	Observed
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*}\rvert$	$0.104^{+0.020}_{-0.016}$	0.103	$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)}\rvert$	$0.122^{+0.023}_{-0.018}$	0.123	$t \to u\gamma$ RH	$1.20^{+0.50}_{-0.33}$	1.22
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*}\rvert$	$0.205^{+0.037}_{-0.031}$	0.227	$t \to c\gamma$ LH	$3.40^{+1.35}_{-0.95}$	4.16
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)}\rvert$	$0.214^{+0.039}_{-0.032}$	0.235	$t \to c\gamma$ RH	$3.70^{+1.47}_{-1.03}$	4.46

- Major systematic: statistical uncertainty
- Factor of 3.3 – 5.4 improvement wrt ATLAS 13 TeV 81 fb^{-1} results
  - More signal region, more optimised analysis and higher luminosity

$t\bar{t}t\bar{t}$ production

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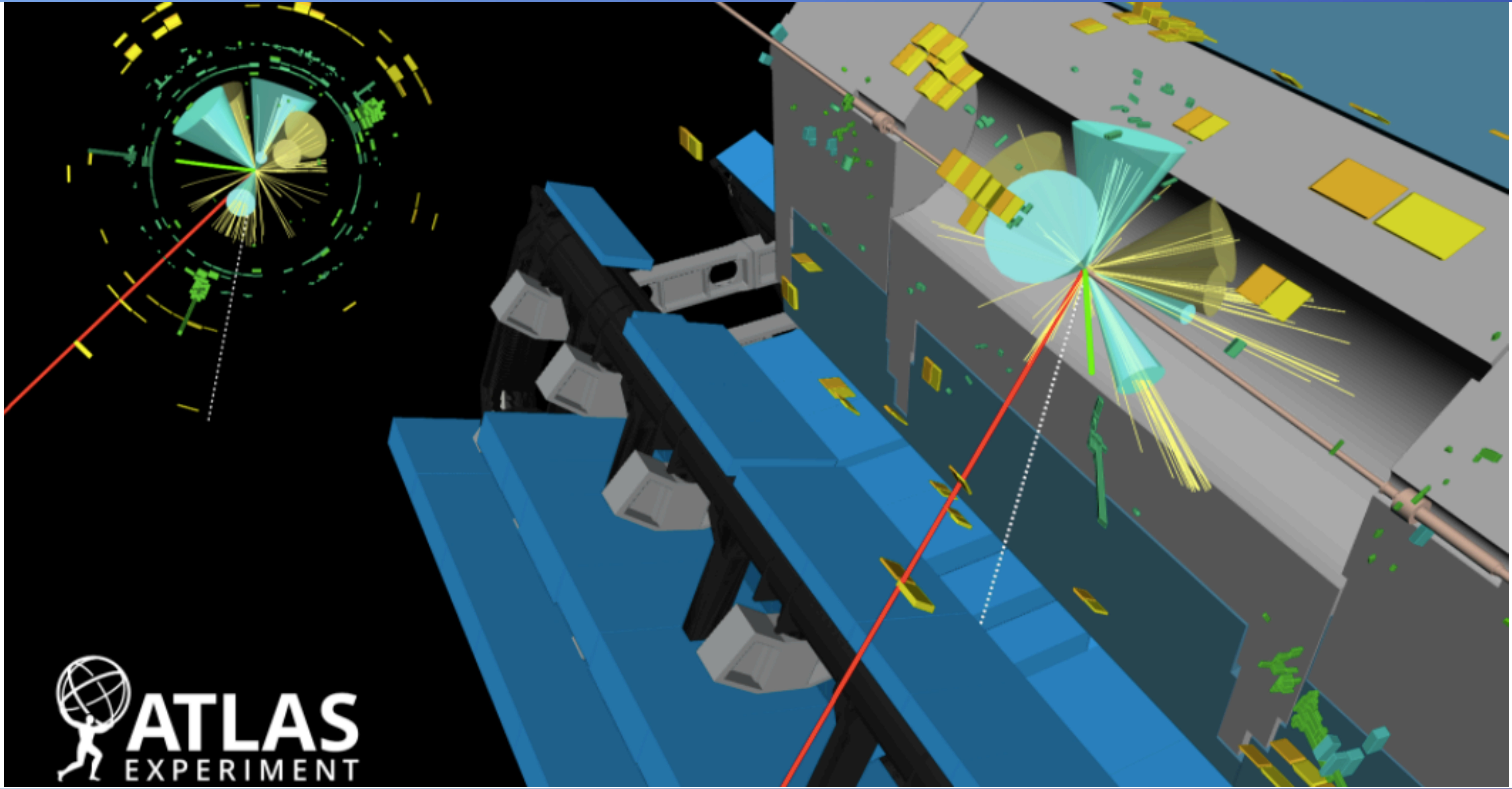
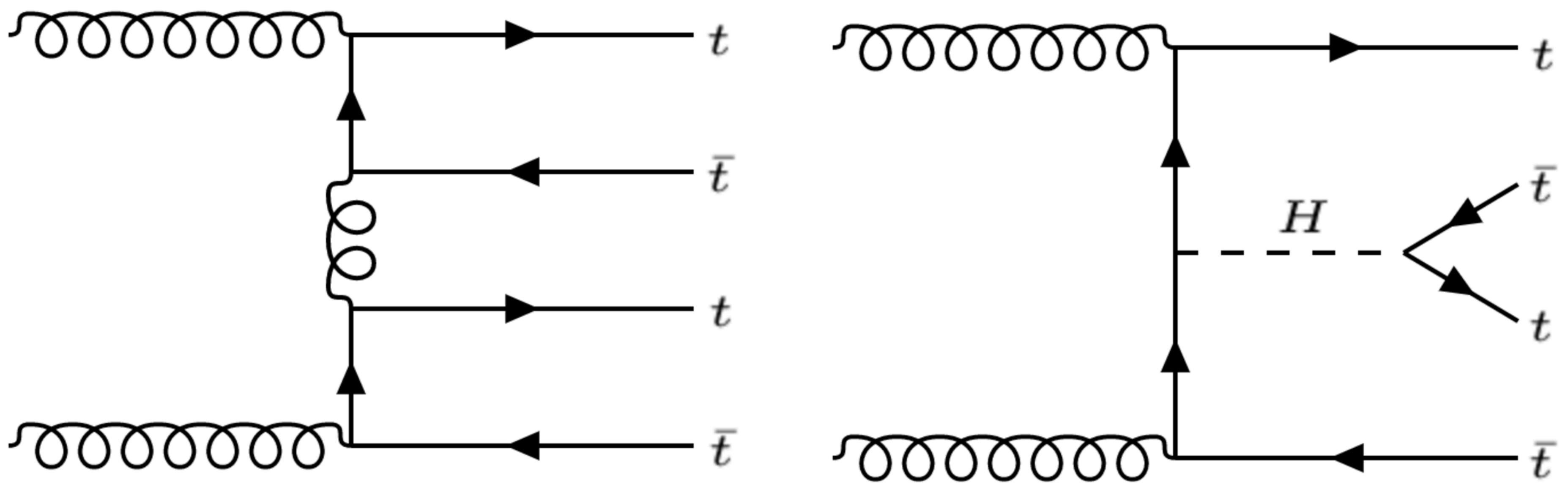
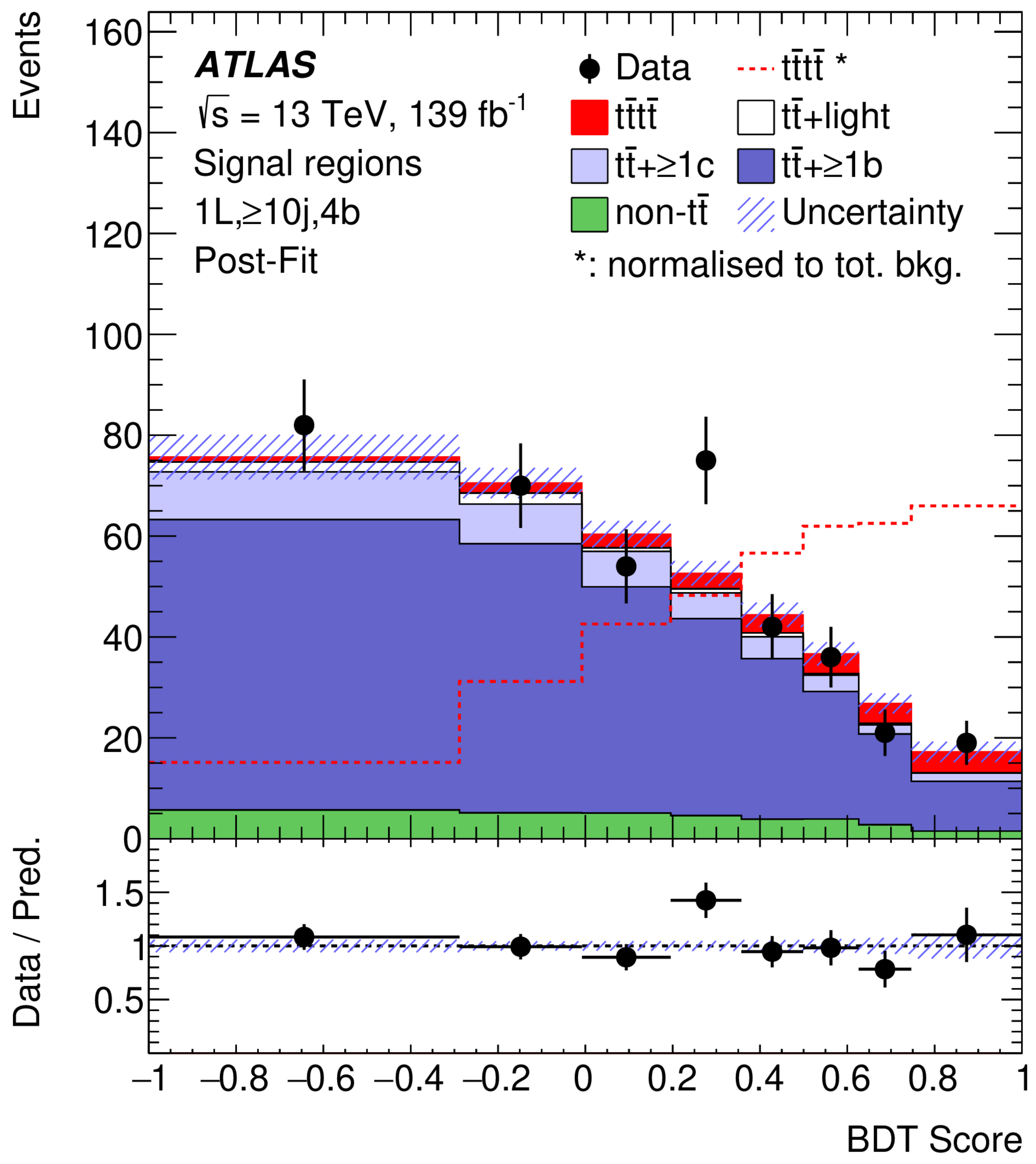


$t\bar{t}t\bar{t}$ production

- **Measurements done in the all of the leptonic final states**
  - SS dilepton and multi-lepton channel (**2LSS/ML**) -> Eur. Phys. J. C 80 (2020)
  - single-lepton and OS dilepton channel (**1L/2LOS**) -> this talk
- Never observed by ATLAS or CMS yet





- BDT that is used to separate the signal from the background
- Targeting events with high jet and b-jet multiplicities
  - 4-top final state features 10 (8) jets in 1L (2LOS) and 4 b-jets at truth level
- $t\bar{t}$+jets background is estimated using corrected MC simulations

$t\bar{t}t\bar{t}$ production

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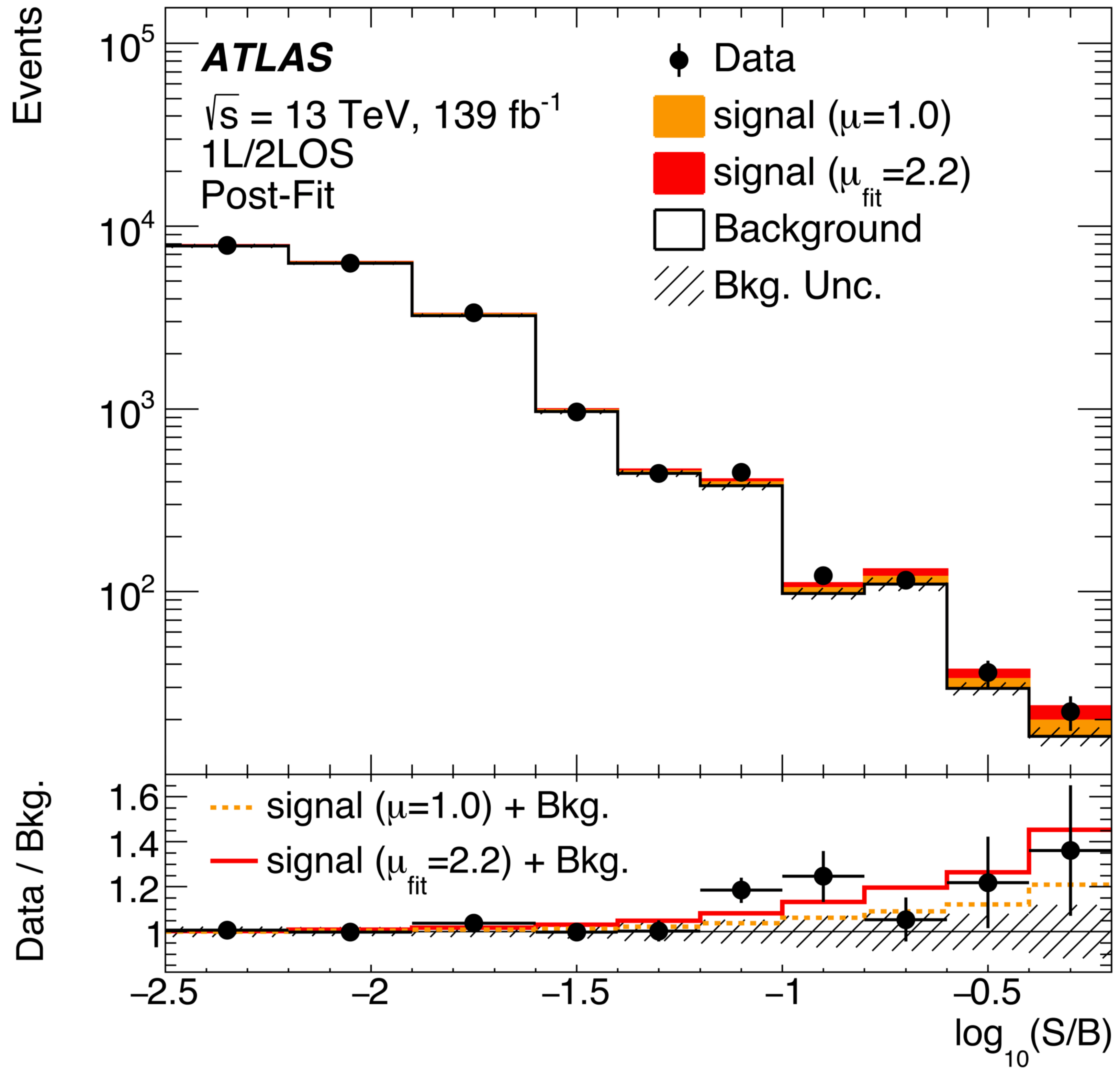
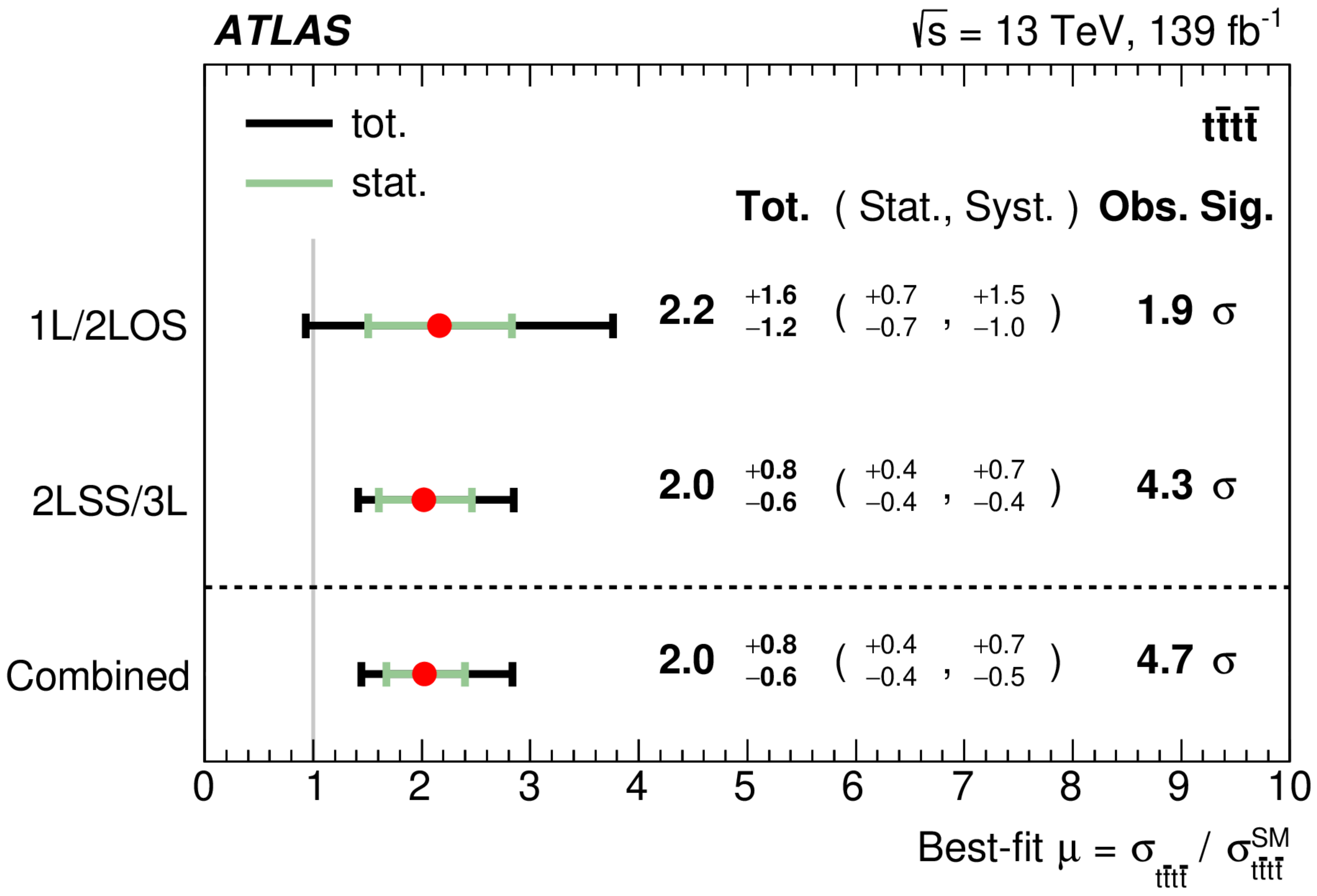
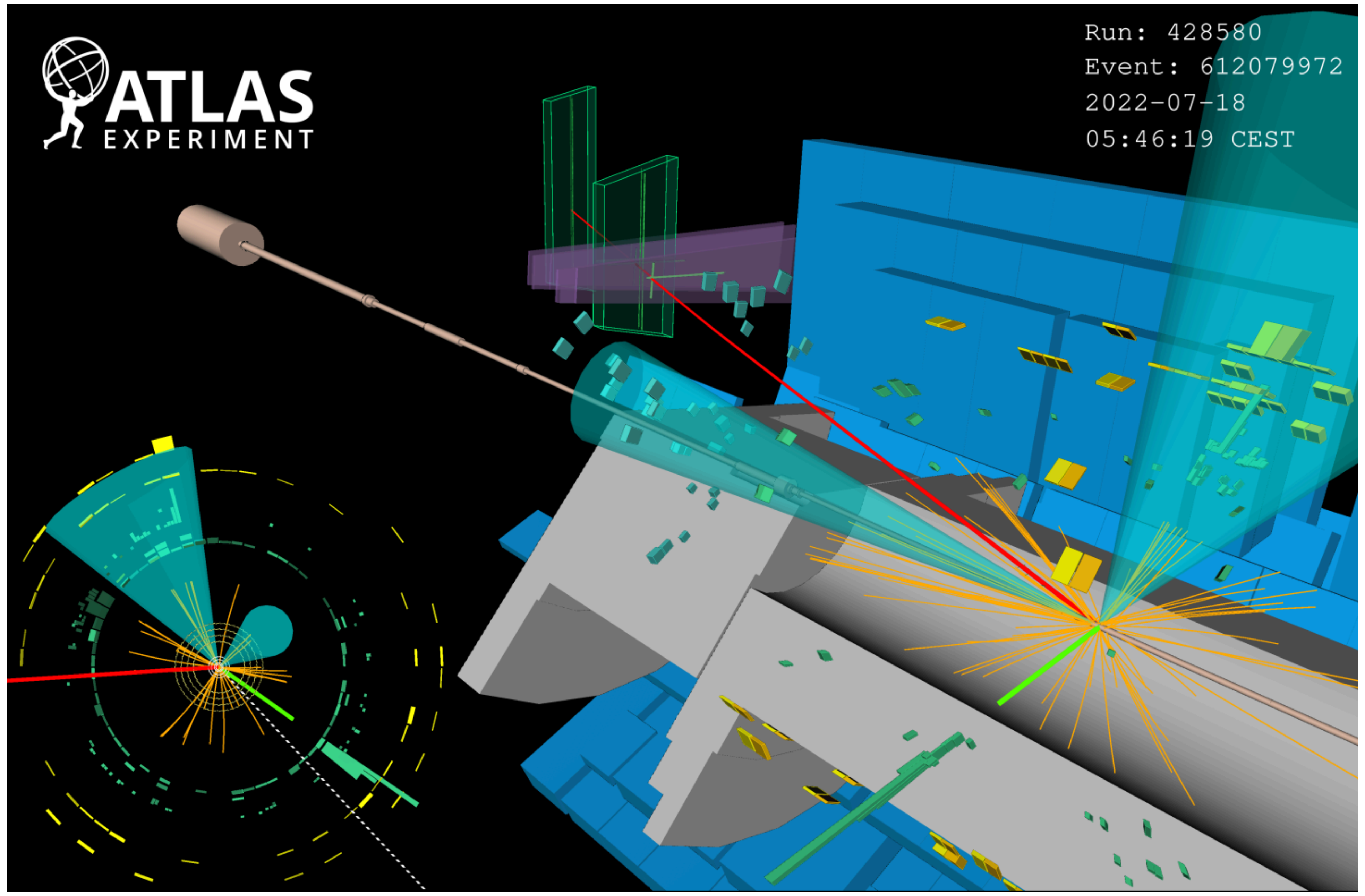




- Measured cross section for 1L/2LOS : $\sigma_{t\bar{t}t\bar{t}} = 26^{+17}_{-15}$ fb
  - With an observed (expected) significance of 1.9 (1.0) σ
  - Uncertainties dominated by 4-top and $t\bar{t}$+HF modelling uncertainties
- Combined cross section with 2LSS/3L analysis : 24^{+7}_{-6} fb
  - With an observed (expected) significance of **4.7** (2.6) **σ**
  - To be compared with the 4.3 σ observed significance from 2LSS/3L analysis

Summary

- The ATLAS experiment has an extensive program of top-quark measurements
- All measurements consistent with the Standard Model predictions
- Large potential to improve the MC configurations for the future
- LHC Run 3 will bring new top quark physics results

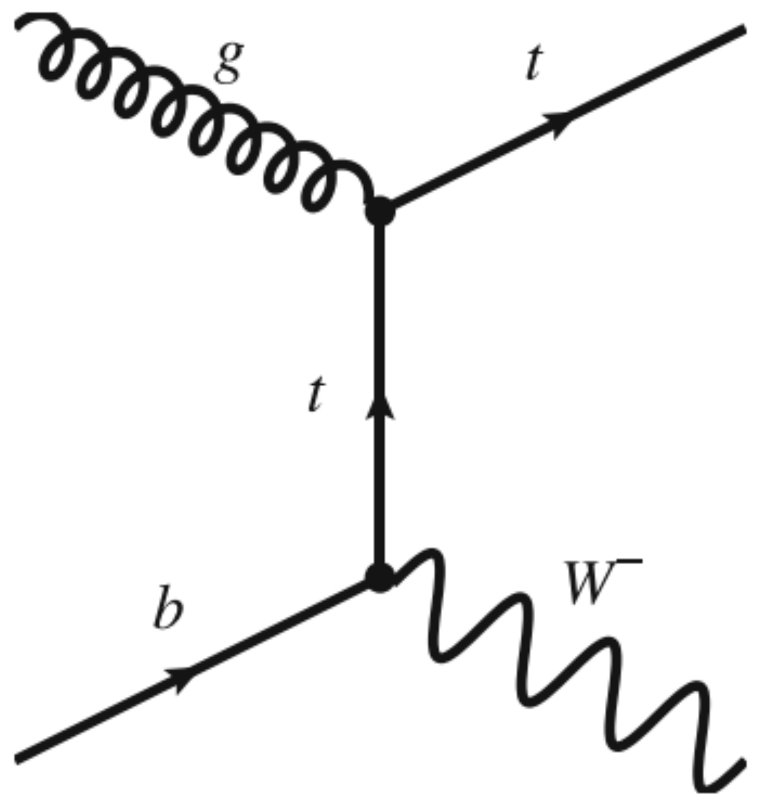


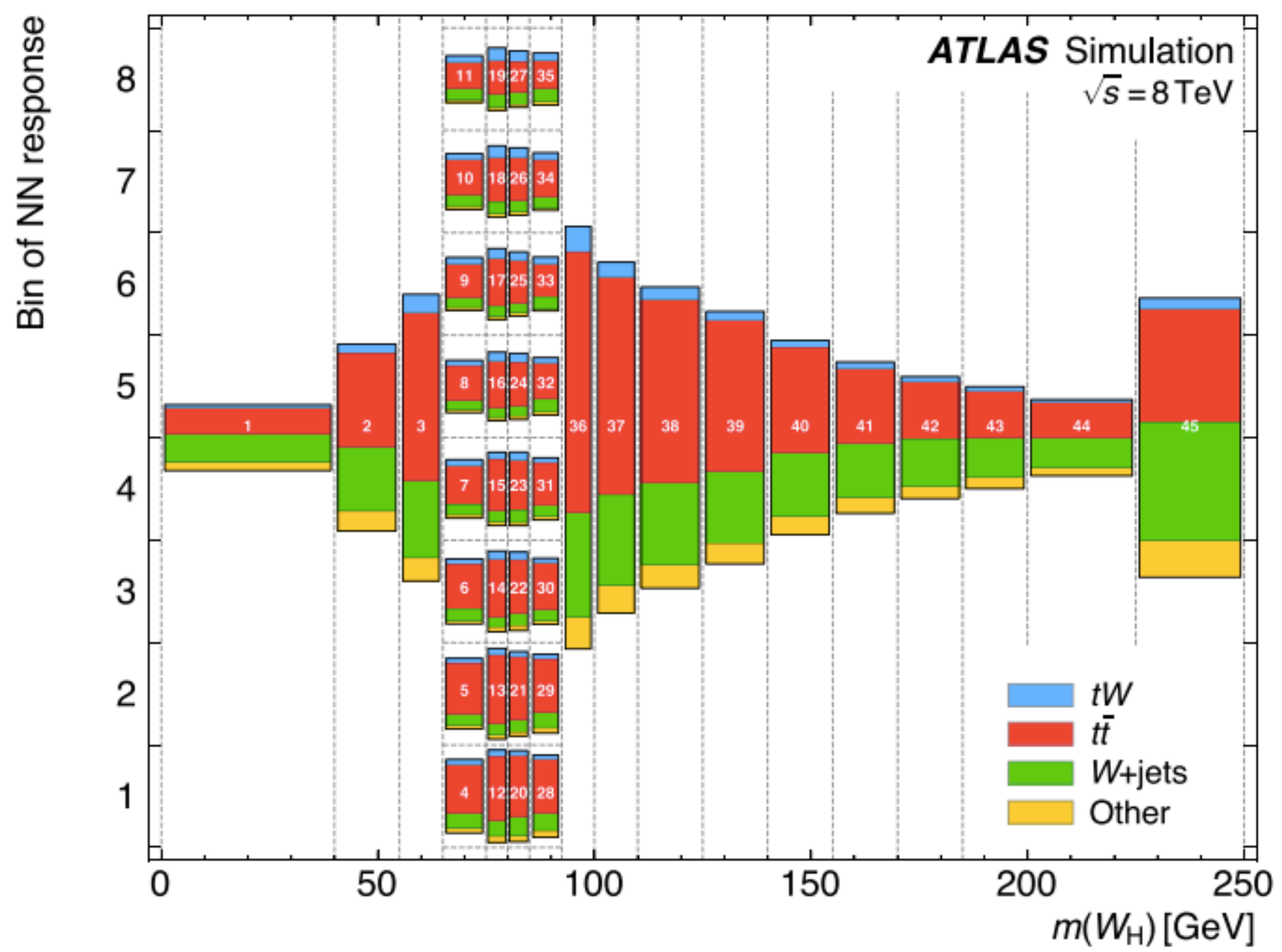
Backup

Wt channel

Eur. Phys. J. C 81 (2021) 720

- Strategy:
  - Signal region: **3j1b**. Jets with $pT > 30$ GeV.
  - A neural network is trained to separate between tW and tt.
  - A 2-dimensional discriminant is constructed with the neural network output in 65 GeV $< m\ WH <$ 92.5 GeV and with the remaining $m(WH)$ variable.
  - The cross section is extracted from a binned profile maximumlikelihood fit to the 2-dimensional discriminant.



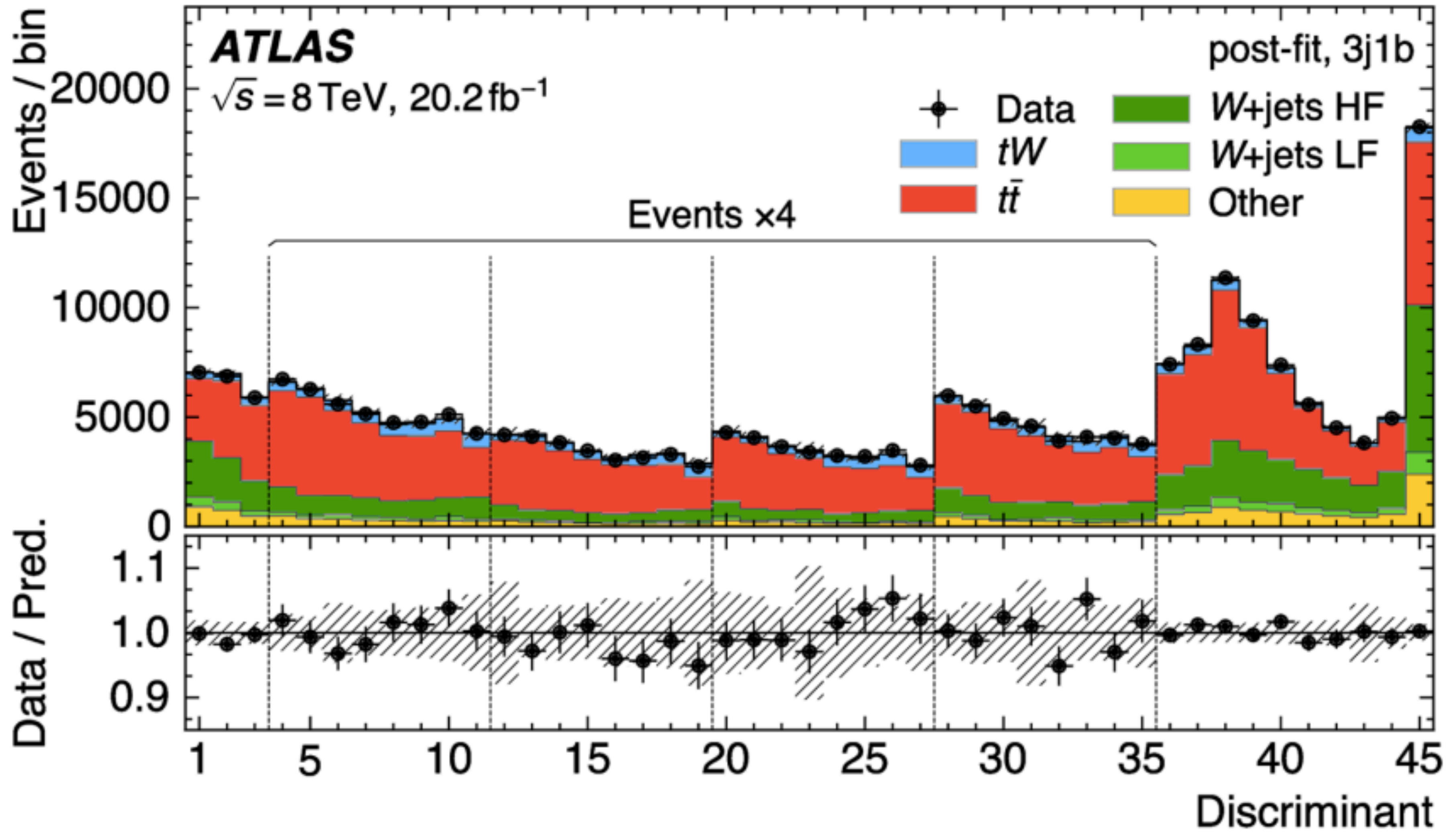


- Measured cross-section :

$$\sigma_{obs.} = 26 \pm 7 \text{ pb}$$

$$\sigma_{pred.} = 22.4 \pm 1.5 \text{ pb}$$

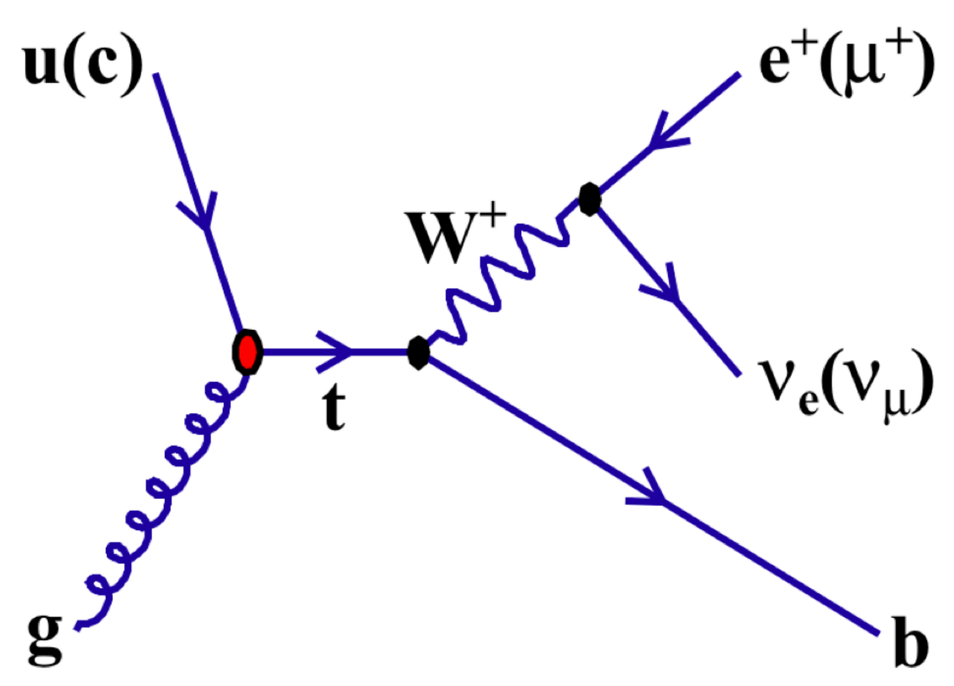
Source	Uncertainty [%]
Jet energy scale	10
b-tagging	8
Jet energy resolution	7
$t\bar{t}$ radiation	10
tW radiation	9
tW–$t\bar{t}$ interference	7

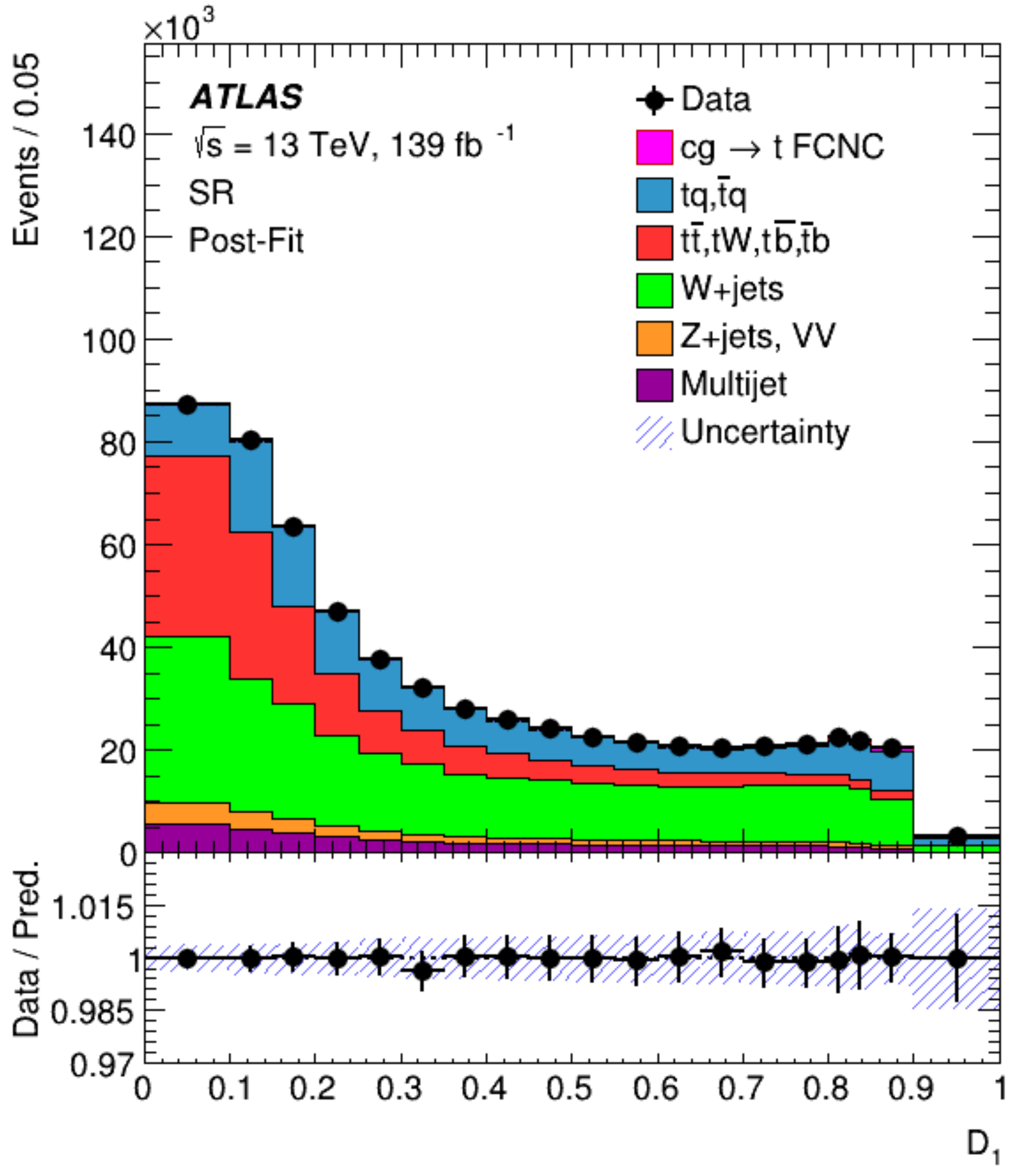


4.5 σ (3.9 σ) observed (expected) significance

FCNC tqg

- Probes single top quark production via FCNC
- Reconstruct top in $t \to e/\mu\, \nu b$ final states, where $t \to \tau\nu b$ may also contribute
  - =1 lepton, ≥1 b-jet, $E_T^{miss} > 30$ GeV, $m_T(W) > 50$ GeV
  - Nr. of b-jet to define validation region, in signal region =1 b-jet





- The analysis targets separate contributions from cgt and ugt
  - Two Neural Network were used to construct two discriminants D_1 (cgt), D_2 (ugt)
- Upper limits on the production:

$$\sigma(ugt) \times \mathcal{B}(t \to Wb) \times \mathcal{B}(W \to \ell\nu) \quad < \quad 3.0\ \text{pb} \qquad 2.4\ \text{pb exp.}$$
$$\sigma(cgt) \times \mathcal{B}(t \to Wb) \times \mathcal{B}(W \to \ell\nu) \quad < \quad 4.7\ \text{pb} \qquad 2.5\ \text{pb exp.}$$
$$\mathcal{B}(W \to \ell\nu) = 0.325$$

- Leading systematics: ugt: related to W+jets process
  cgt: modelling of the parton shower

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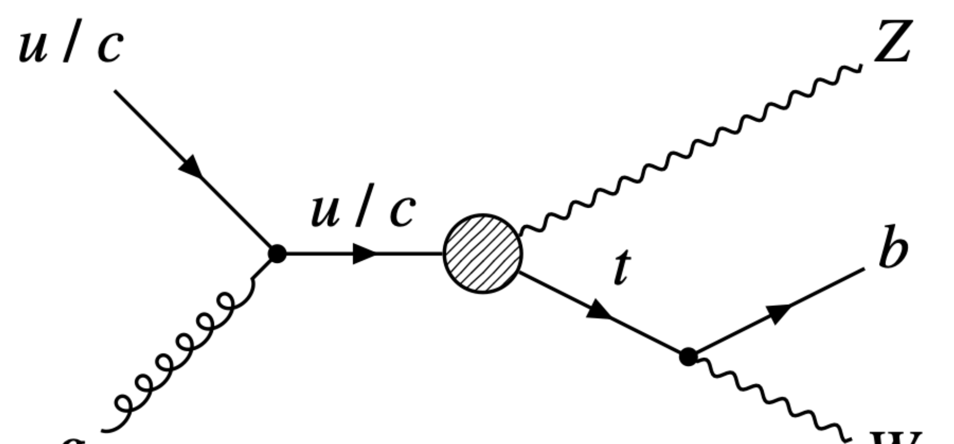
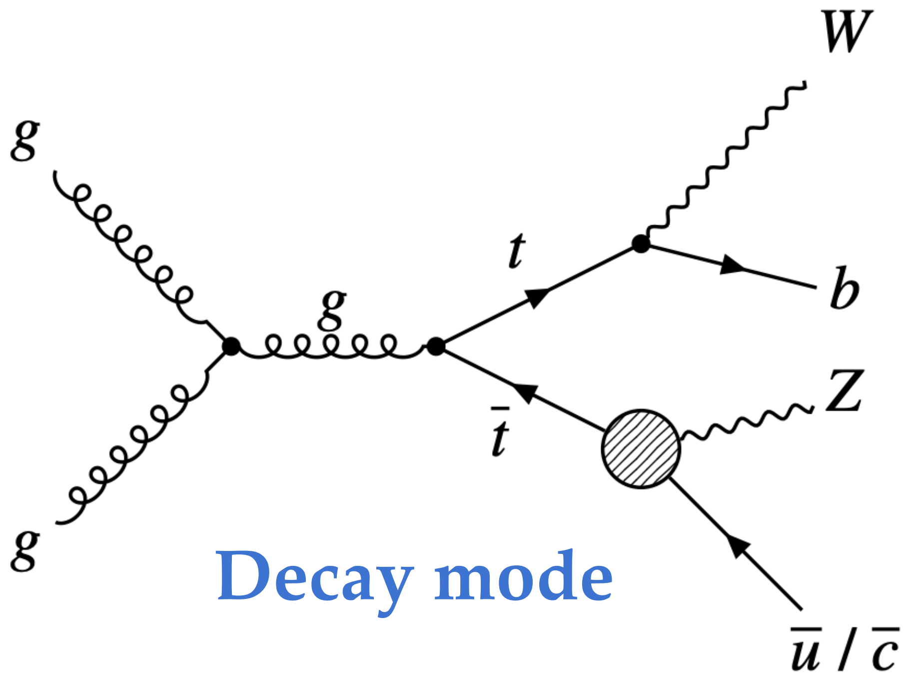
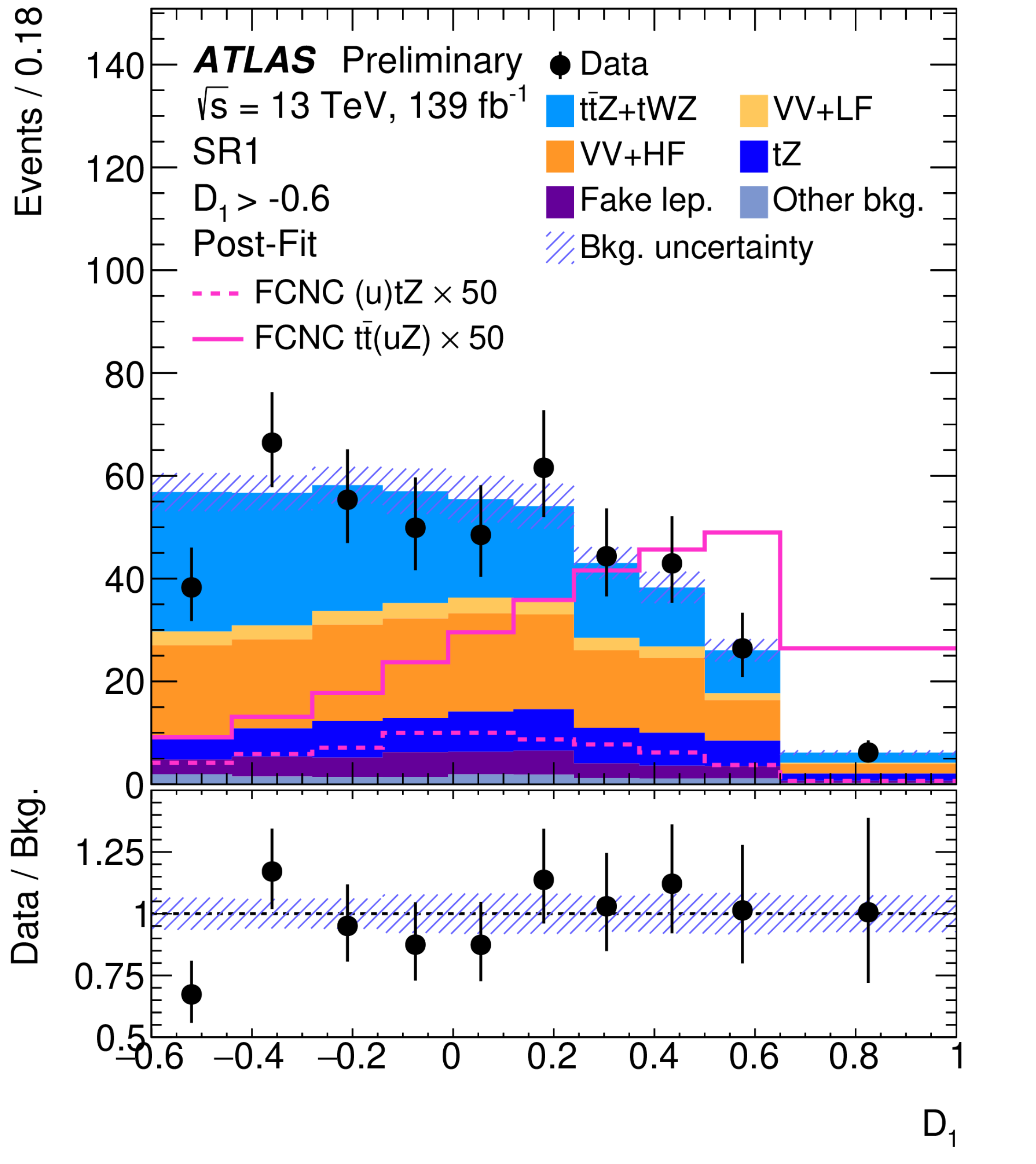
- Target both production and decay of FCNC tqZ vertices:
  - Z→ ll, semi-leptonic top decay ⇒ tri- leptons
- Analysis regions
  - Orthogonality cut applied on reconstructed top mass
  - ≥2 jets, 1 b-jet (SR1) targeting decay mode or ≥1 jet, 1 b-jet (SR2) targeting production mode
  - Gradient BDT was used to better separate signal from backgrounds

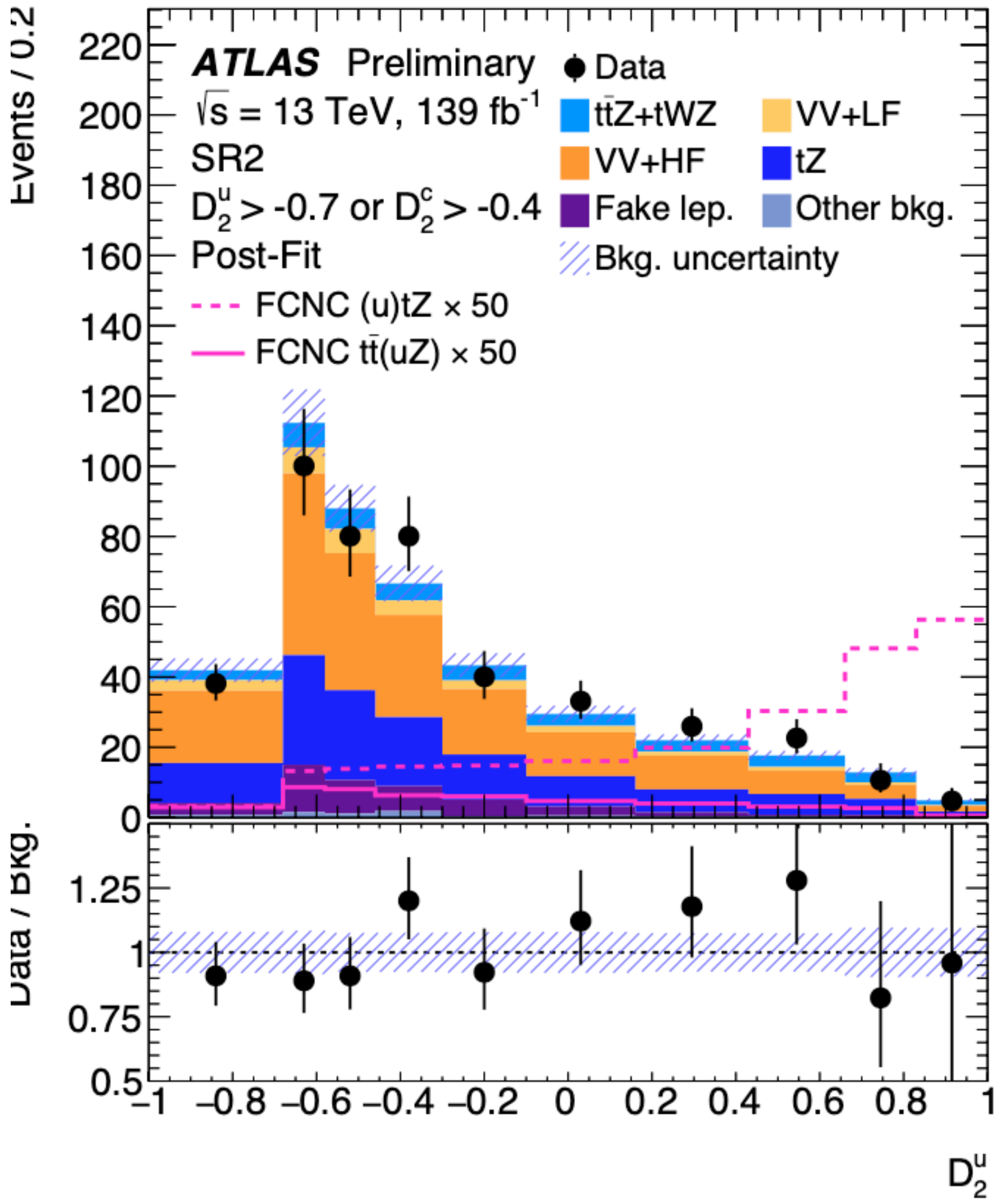


Production mode



Decay mode





Observable	Vertex	Coupling	Observed	Expected
		SR1+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	9.7	$8.6^{+3.6}_{-2.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	9.5	$8.2^{+3.4}_{-2.3}$
		SR2+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	7.8	$6.1^{+2.7}_{-1.7}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	9.0	$6.6^{+2.9}_{-1.8}$
		SRs+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	6.2	$4.9^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	6.6	$5.1^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZc	LH	13	11^{+5}_{-3}
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZc	RH	12	10^{+4}_{-3}

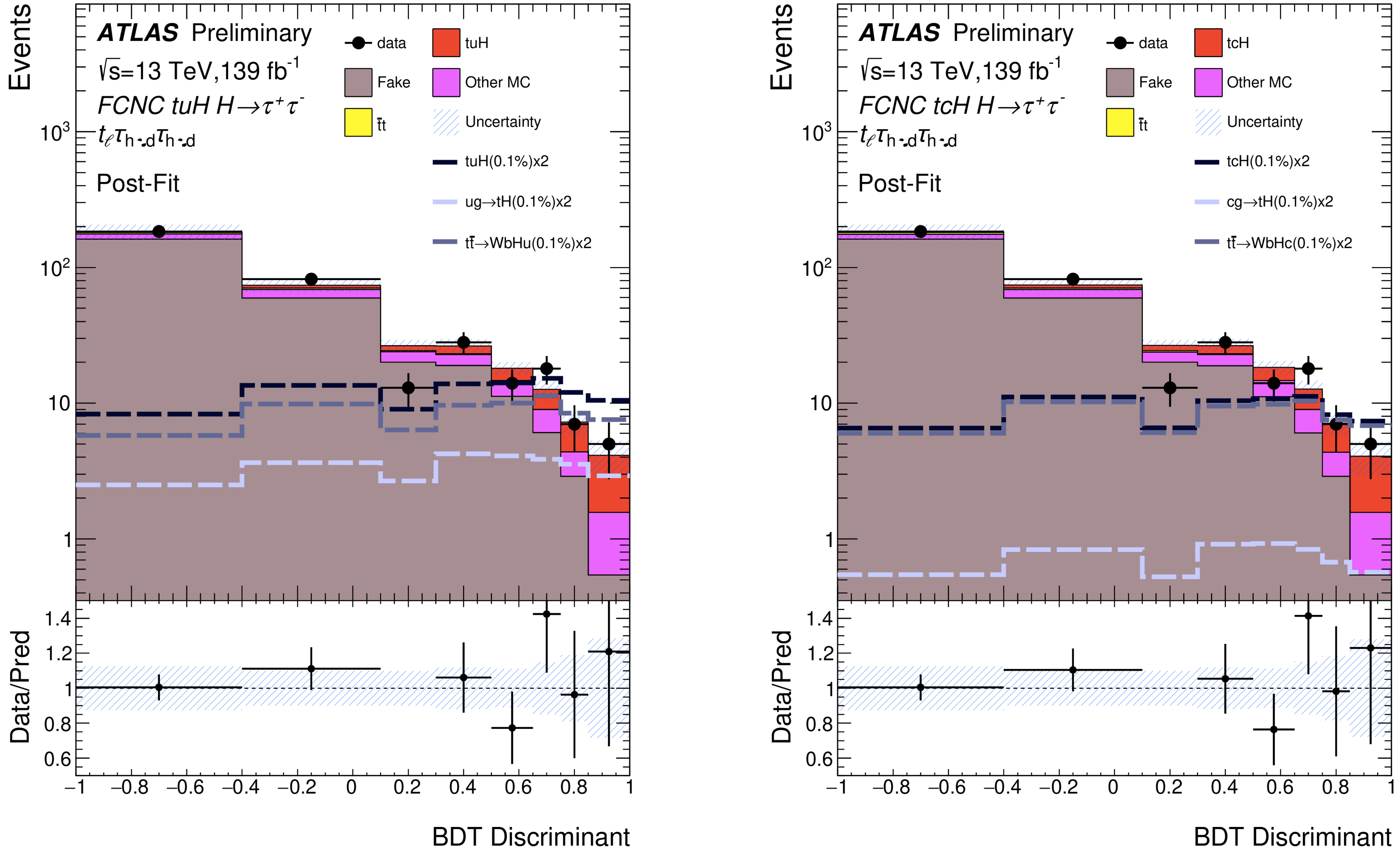
- Upper limits on branching ratios were improved with respect to the previous results by factor 2 - 5

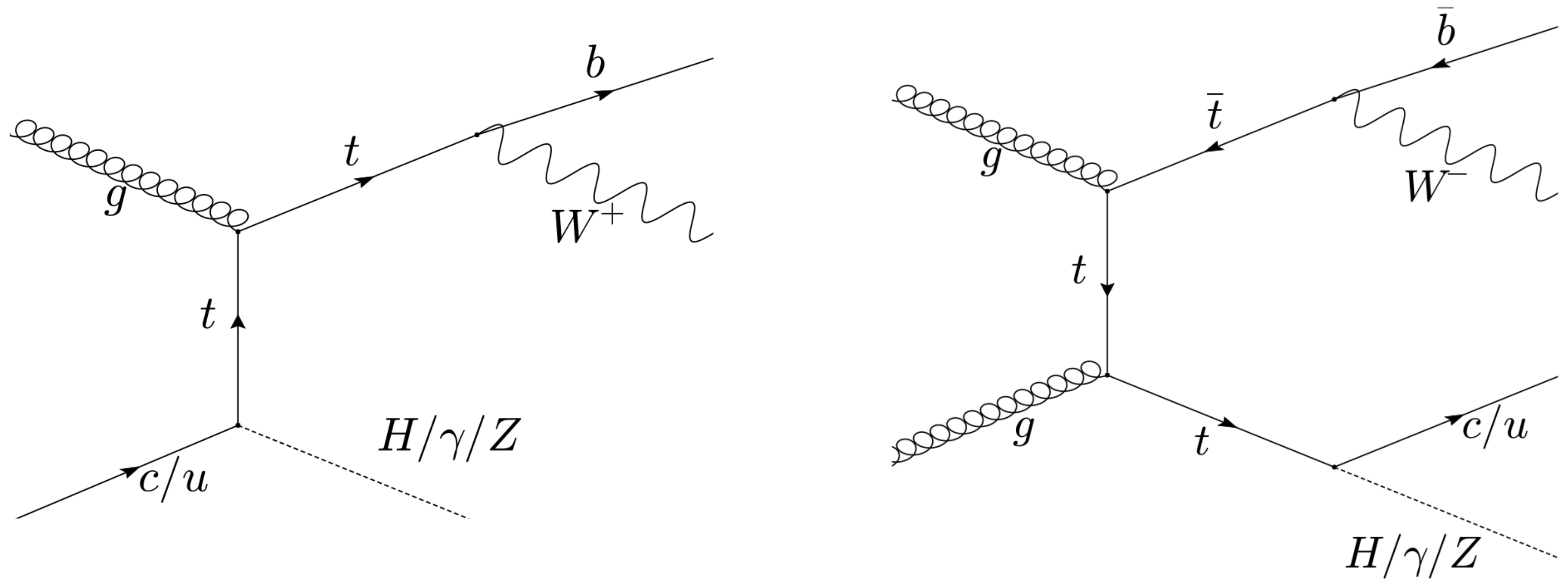
- Dominant systematic: statistical uncertainty

FCNC $H \to \tau^+ \tau^-$

arxiv:2208.11415
submitted to JHEP

- Explored both production and decay of FCNC tqH vertices
  - Top quark: leptonic or hadronic decay
  - $H \to \tau\tau$: $\tau_{had}\,\tau_{had}$ or $\tau_{lep}\,\tau_{had}$ (depending on τ-lepton decay)





- Analysis regions
  - Employ seven signal regions in a combination of top and di-tau decay, and additional jets
  - BDT is trained in each of the SR to separate signal from SM background
- Background estimation
  - Fake τ: estimate a transfer factor in CR
  - Others: Monte-Carlo simulation

FCNC $H \to \tau^+ \tau^-$

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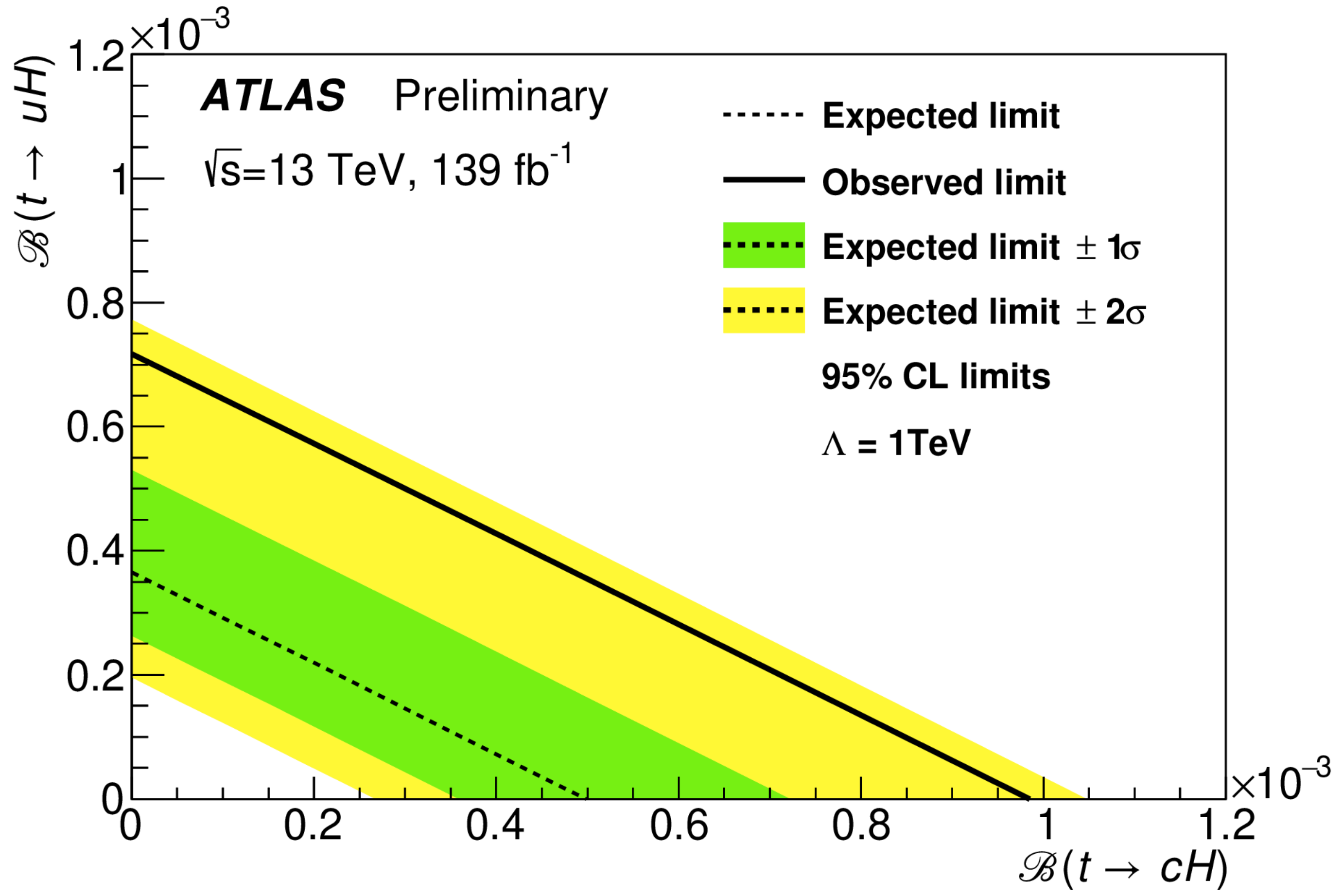
- Upper limits of BR:

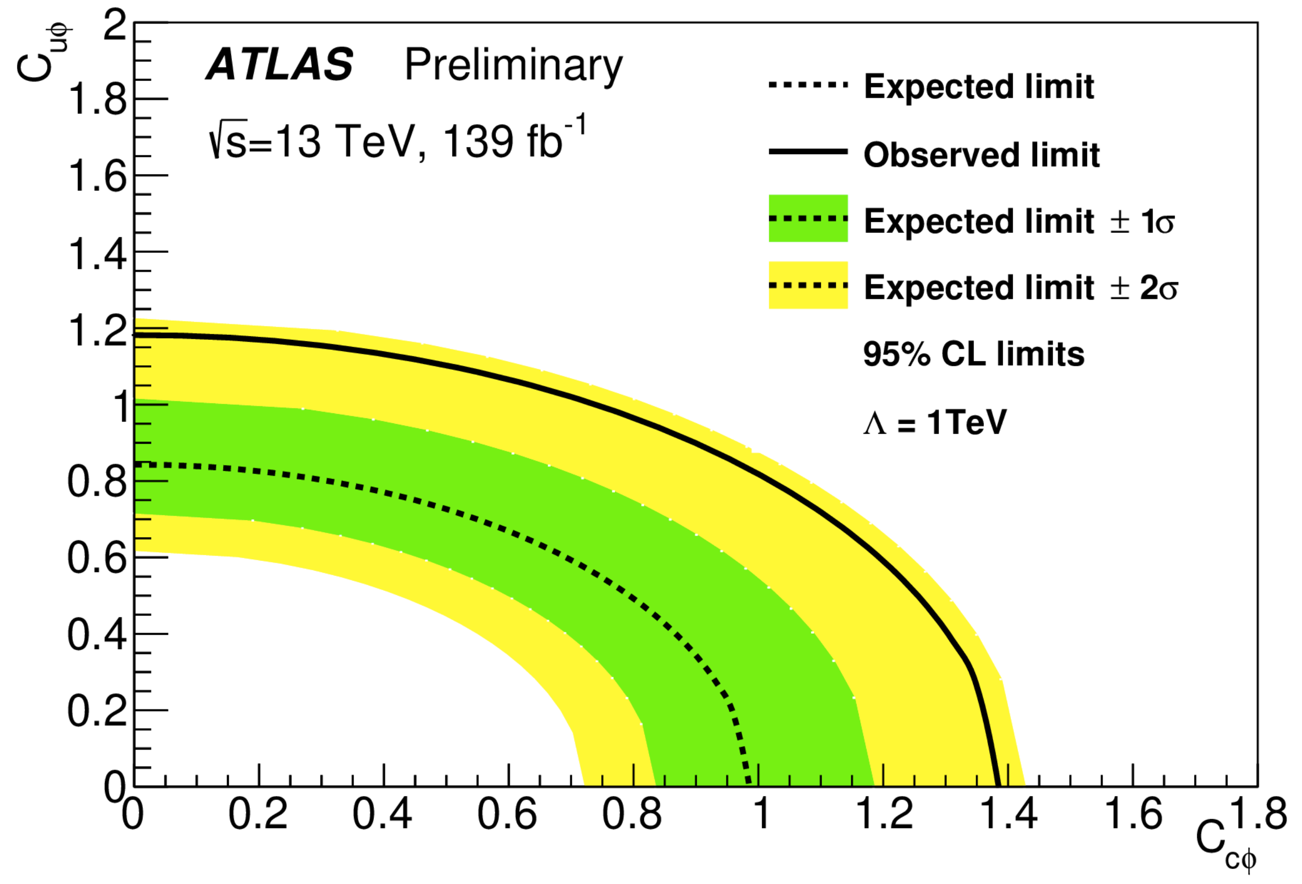
$$\mathcal{B}(t \to cH) < 9.9 \times 10^{-4}\,(5.0^{+2.2}_{-1.4} \times 10^{-4}),\ \text{assuming}\ \mathcal{B}(t \to uH) = 0$$

$$\mathcal{B}(t \to uH) < 7.2 \times 10^{-4}\,(3.6^{+1.7}_{-1.0} \times 10^{-4}),\ \text{assuming}\ \mathcal{B}(t \to cH) = 0$$

- Limits translate to tqH Wilson coefficients: $C_{c\phi} < 1.38\,(0.97)$ and $C_{u\phi} < 1.18\,(0.83)$

- 2D contours:



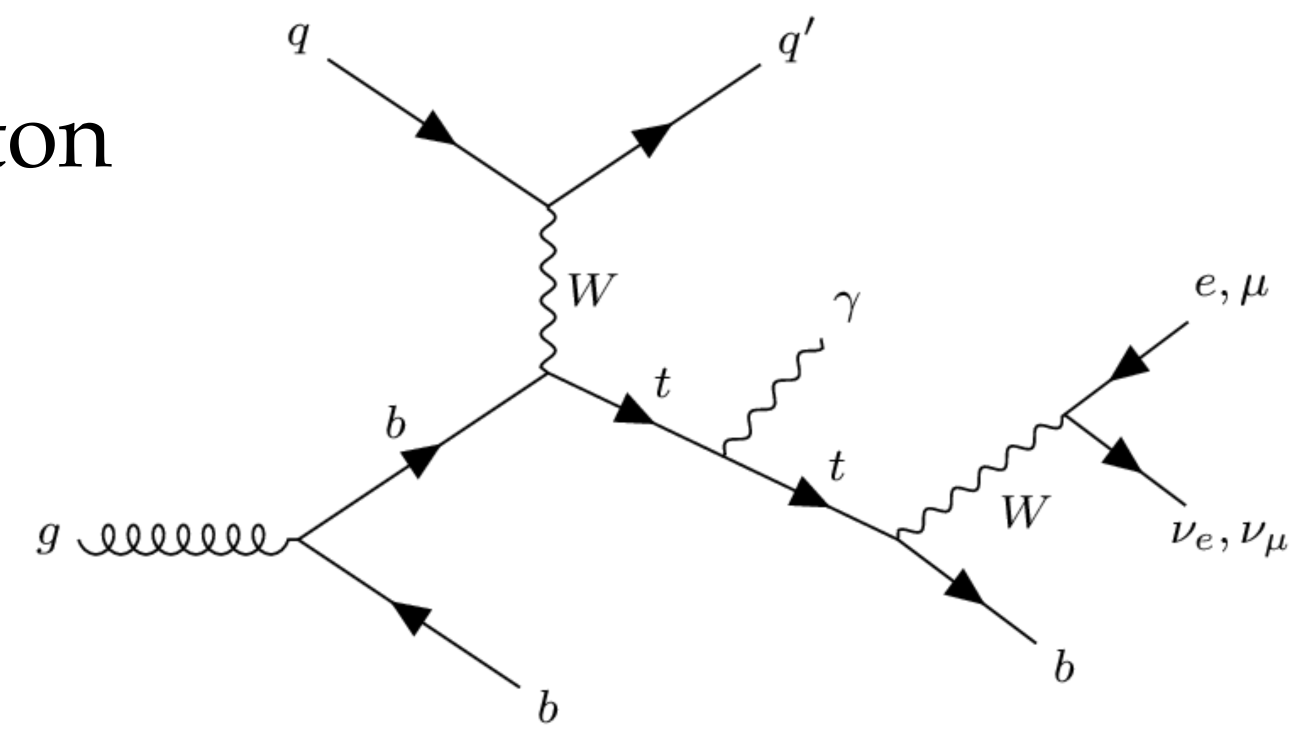


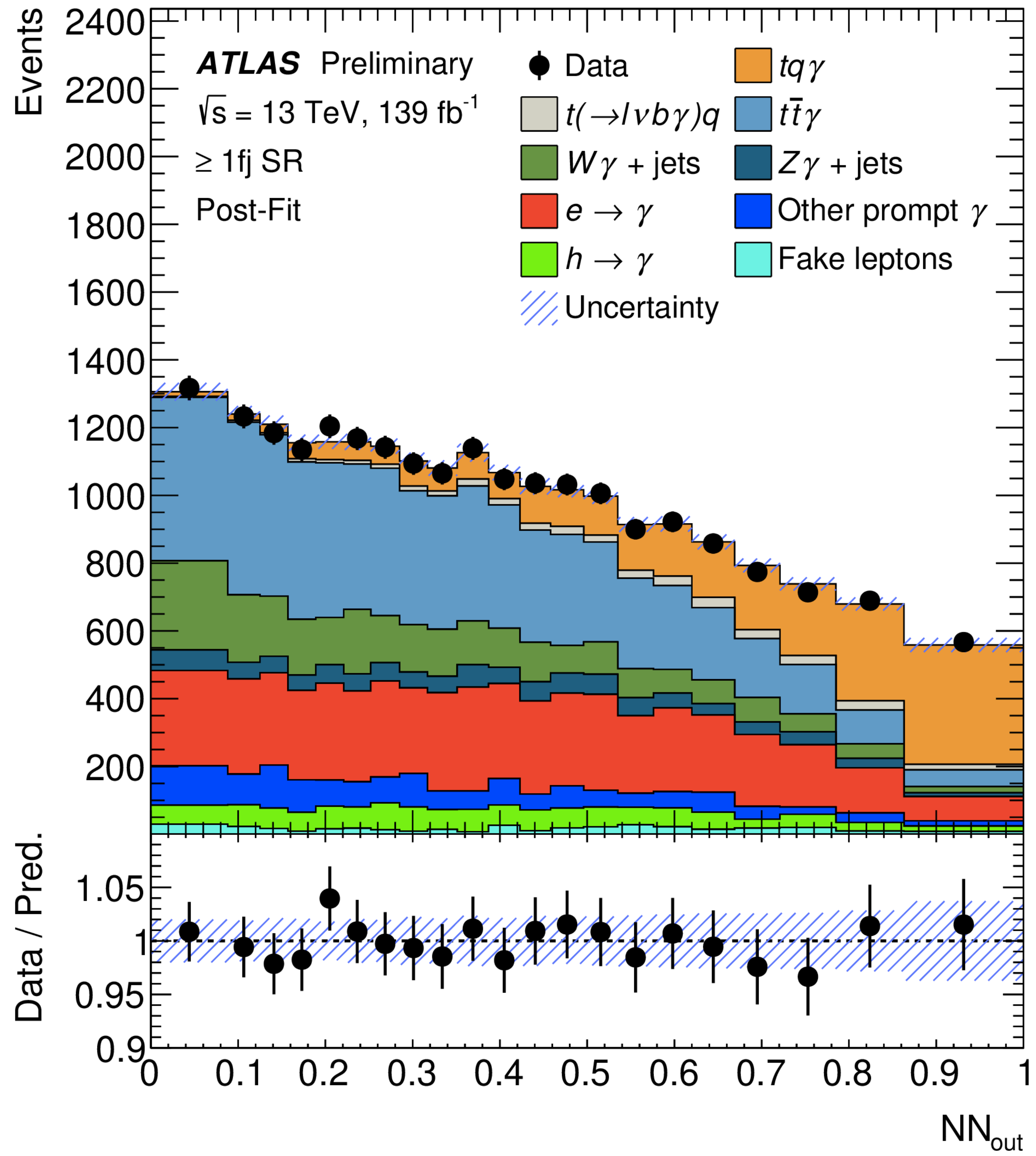
- Major systematic: statistical uncertainty
- A slight excess of data is observed above background with a significance of 2.3 σ
- A factor of 5 improvement wrt ATLAS 13 TeV 36 fb^{-1} results

SM tqγ

ATLAS-CONF-2022-013

- First observation of t-channel single top quark production in association with a photon
  - tqγ (prod) with observed (expected) significance: 9.1 (6.7) σ
- Sensitive to EW couplings of the top quark (esp. top-γ vertex)





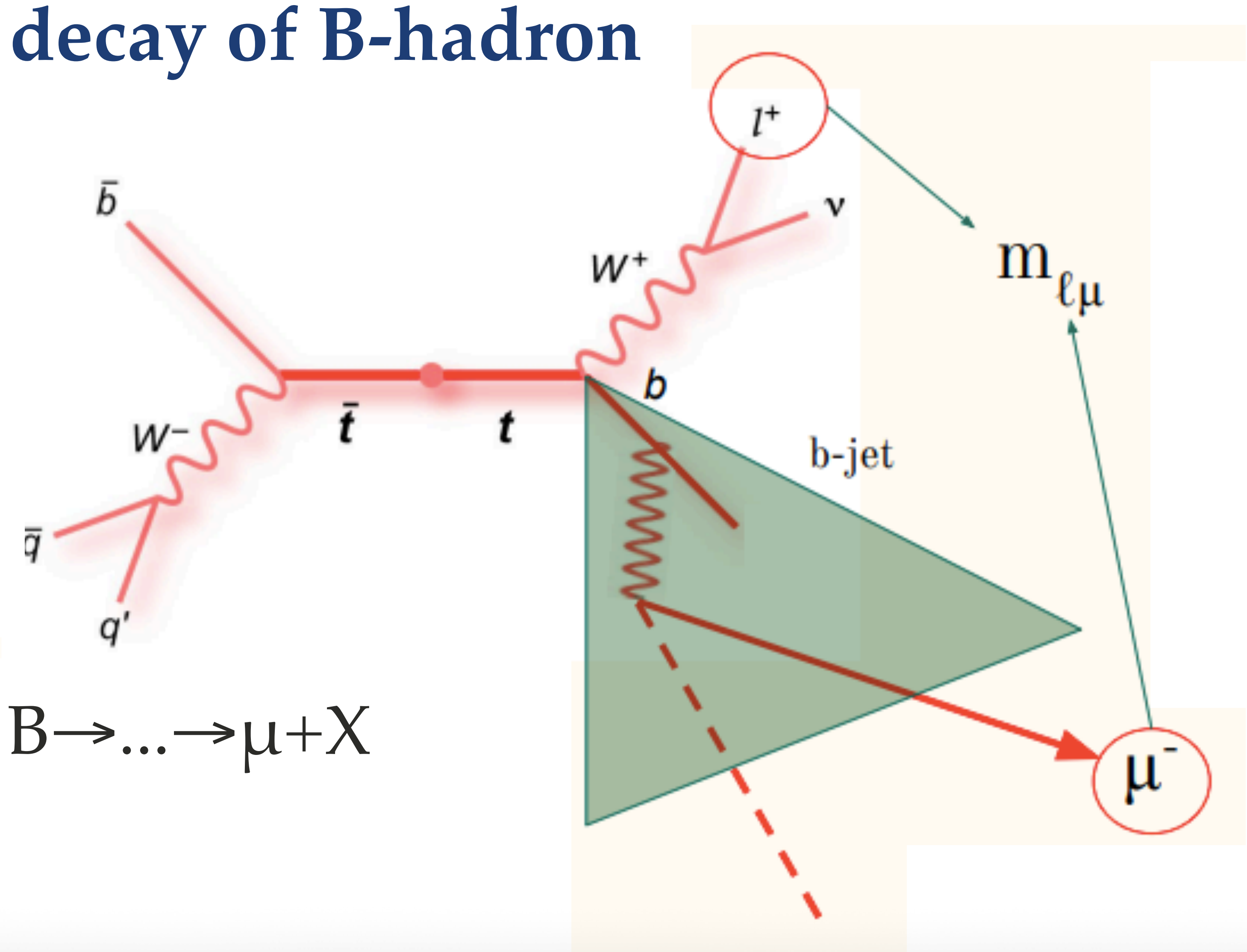
Cross section measurement

- Parton level: $\sigma_{tq\gamma} \times B(t \to l\nu b)$ = 580 ± 19 (stat.) ± 63 (syst.) fb
- Particle level: $\sigma_{tq\gamma} \times B(t \to l\nu b) + \sigma_{t(\to l\nu b\gamma)q}$ = 287 ± 8 (stat.) ± 31 (syst.) fb

- ATLAS measurements consistently higher than the prediction by ~ 40%
- Major systematic uncertainties come from
  - background modelling: $t\bar{t}\gamma$ ~ 6%; $t\bar{t}$ ~ 3%
  - MC statistics: tqγ ~ 3%; all other processes ~ 3%

Top mass measurement

Semi-leptonic decay of B-hadron



BR=20% for B→...→μ+X

Top mass using soft muon tag

Invariant mass $m_{l\mu}$ sensitive to mt

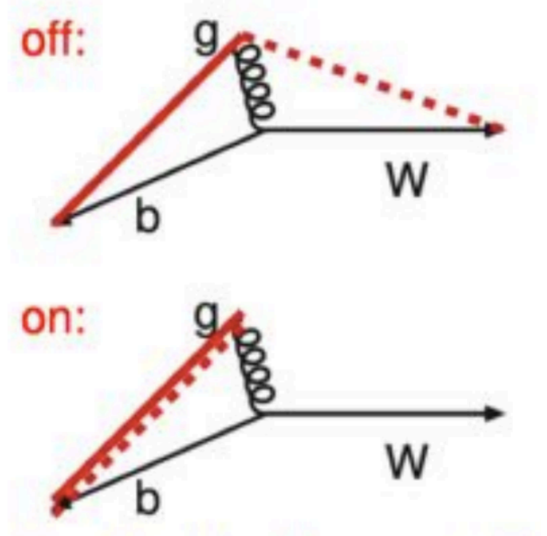
reduced sensitivity to JES

sensitive to fragmentation modelling

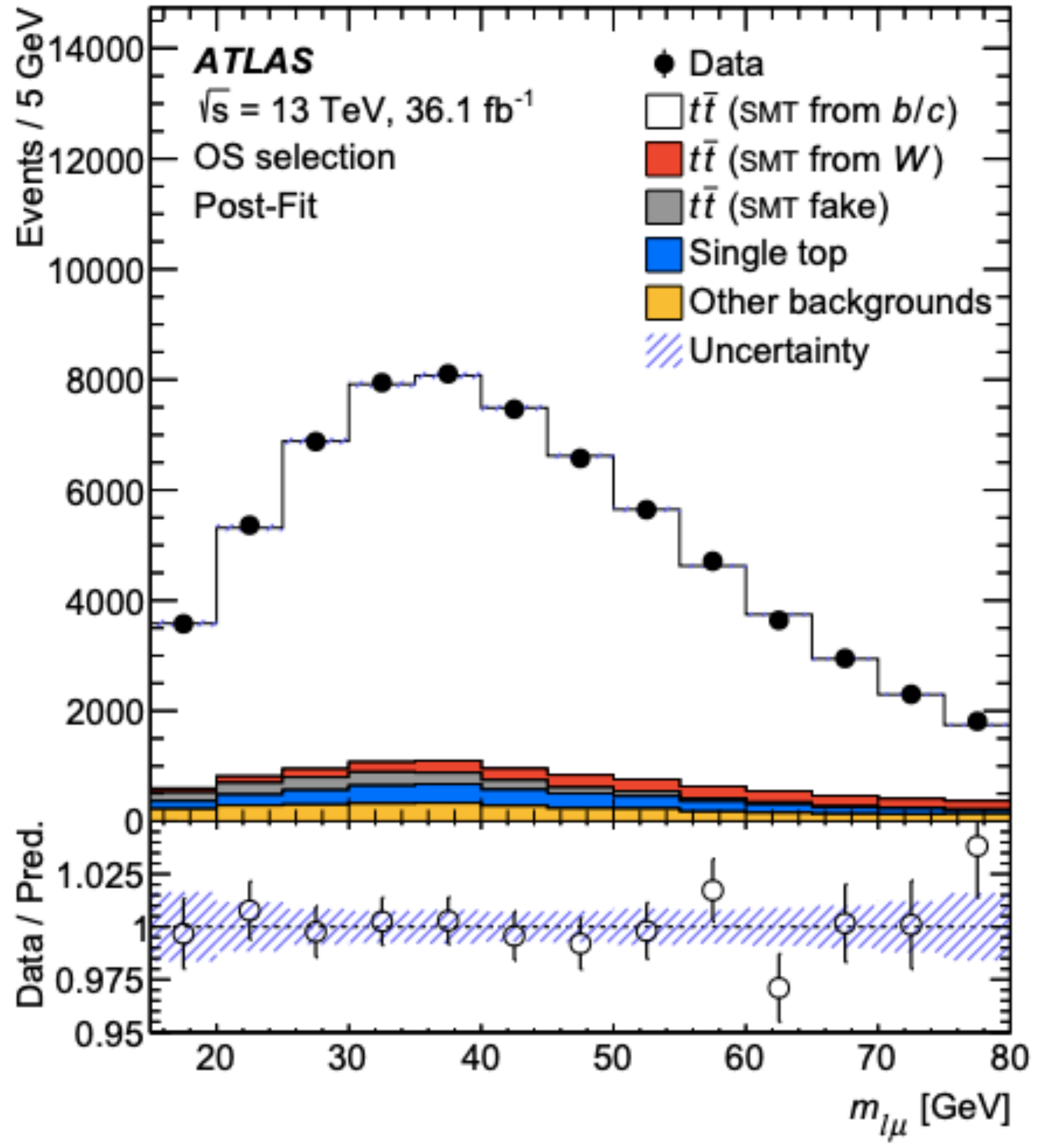
Uncertainty on gluon emission in t→Wb

- impacts PS modelling of gluons from b→gb
- changes energy distribution within jet
- changes jet pT due to out-ofcone radiation → impacts jet- based measurement

recoilToColoured Pythia option

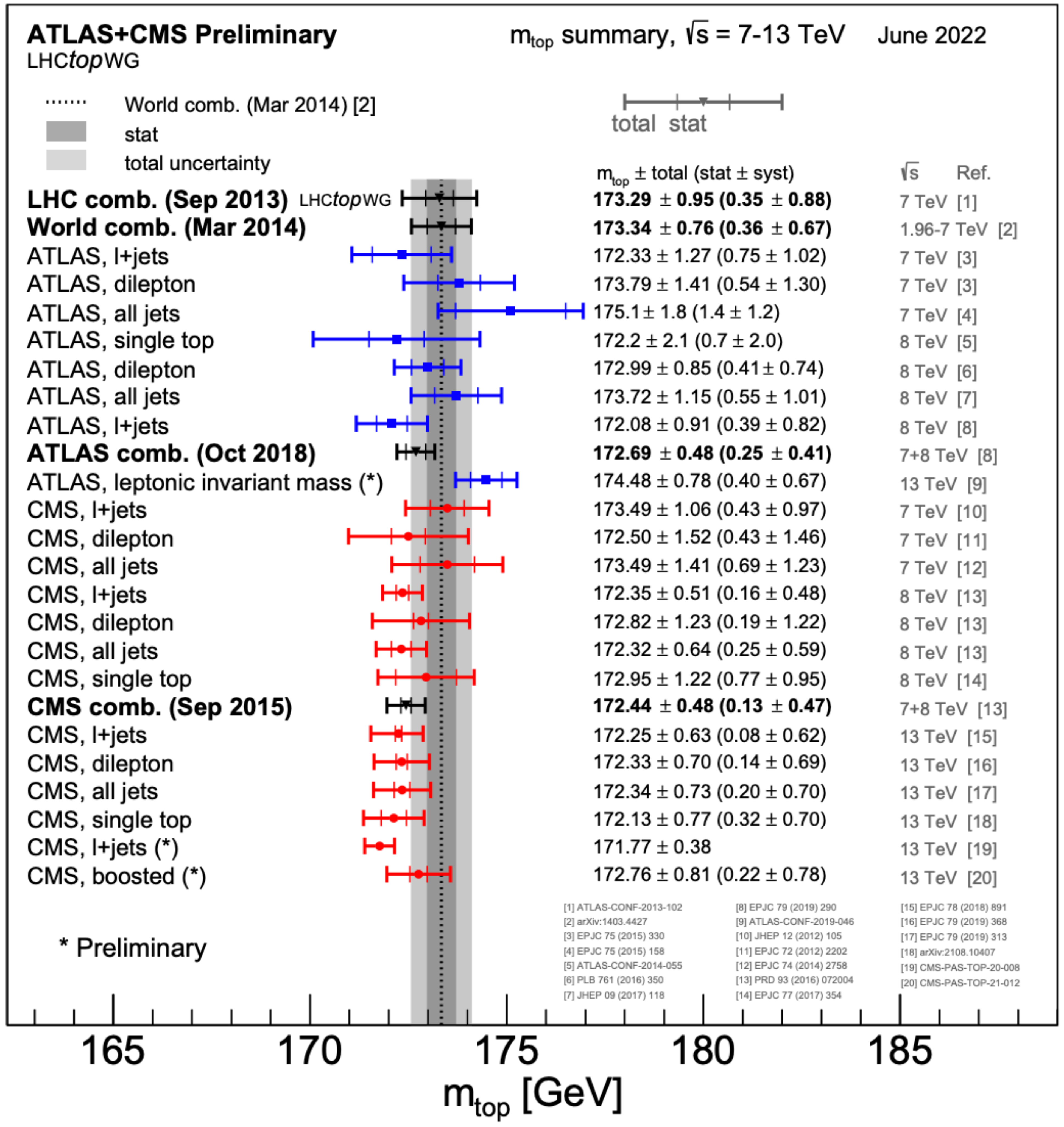


- Final result from ML profiled fit on mℓμ
- consistent at 2σ level with previous results



$$m_t = 174.41 \pm 0.39\,(\text{stat.}) \pm 0.66\,(\text{syst.}) \pm 0.25\,(\text{recoil})\ \text{GeV}$$

Top mass measurement



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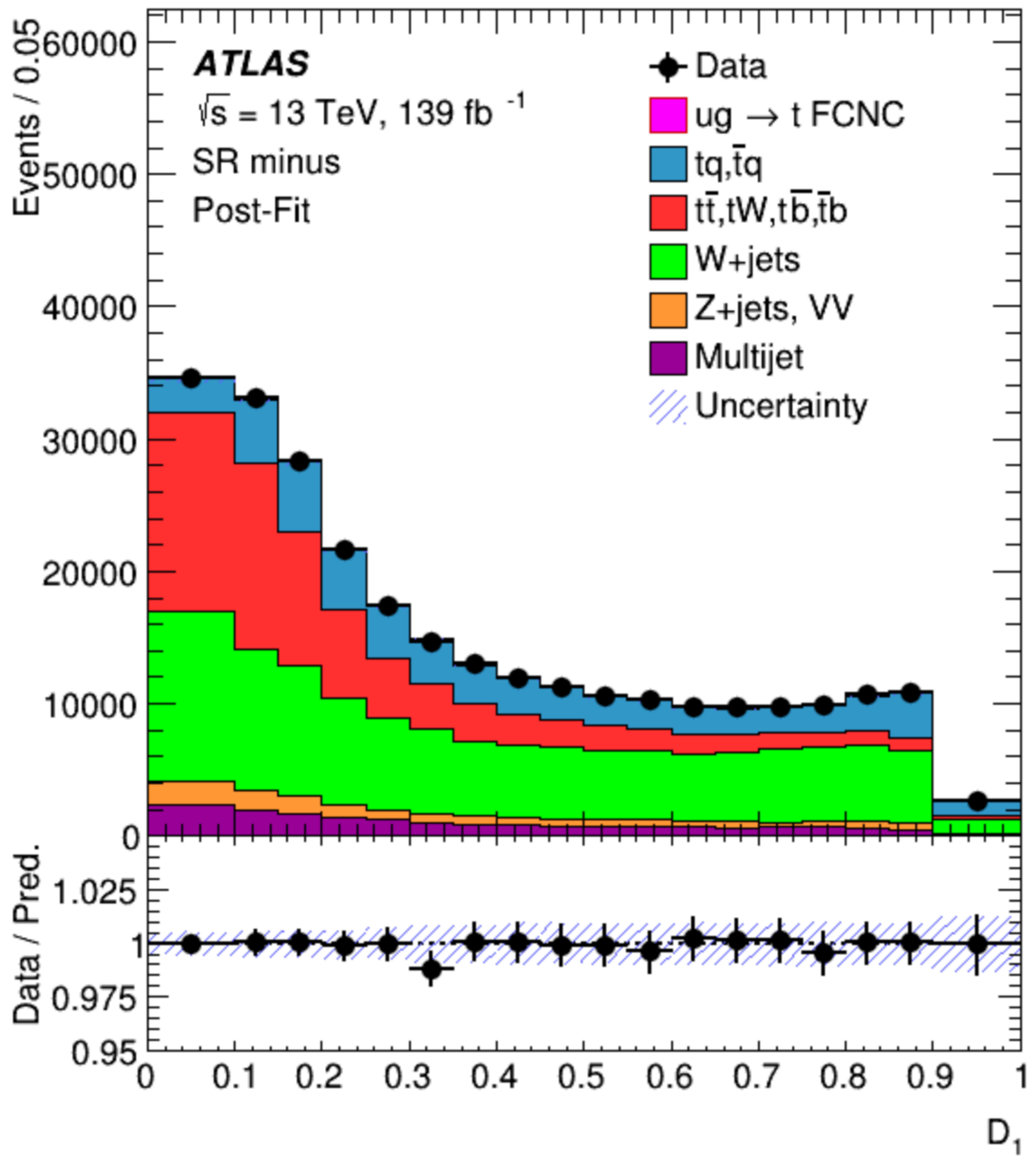
Branching ratios of top FCNC decays

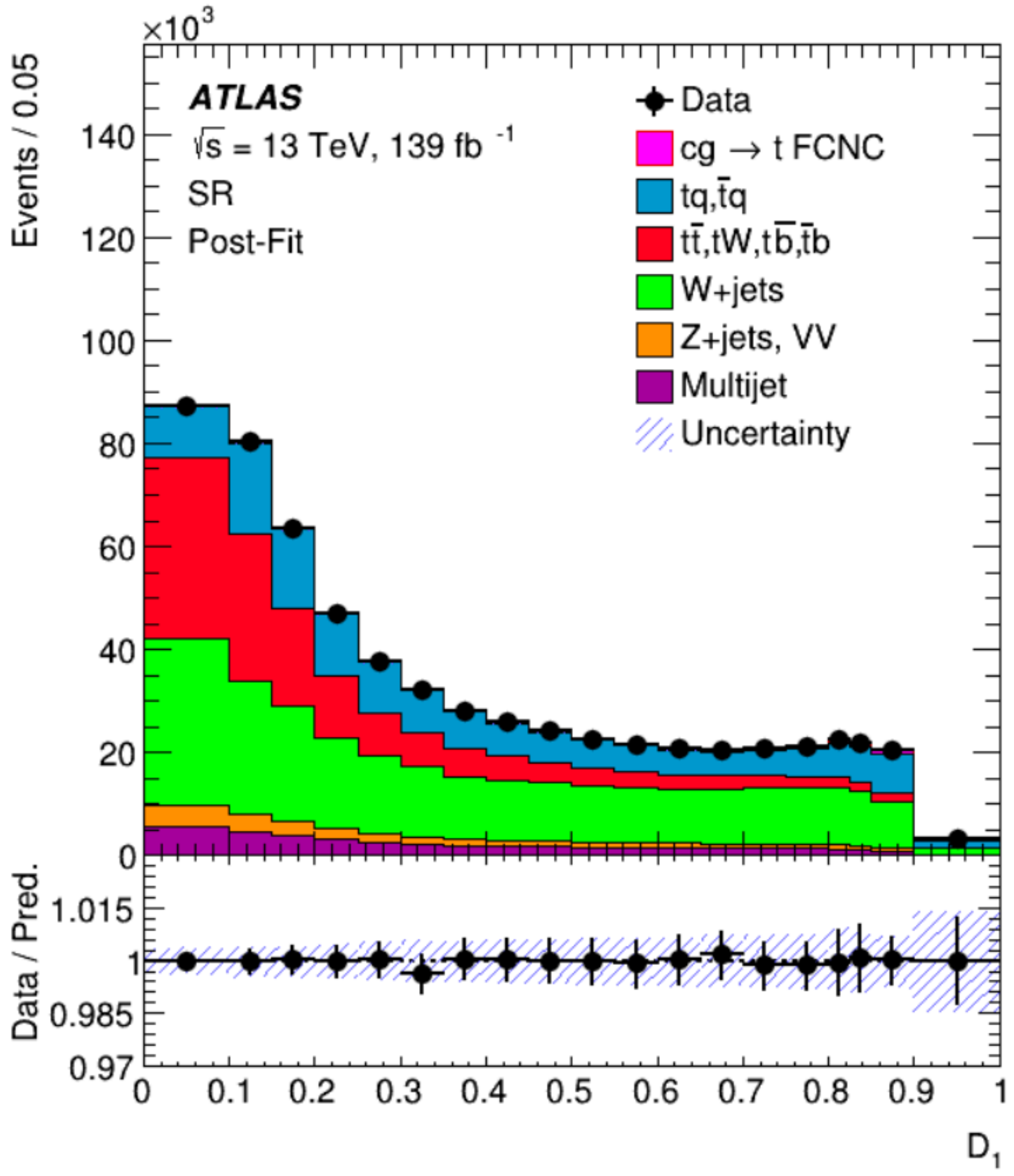
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

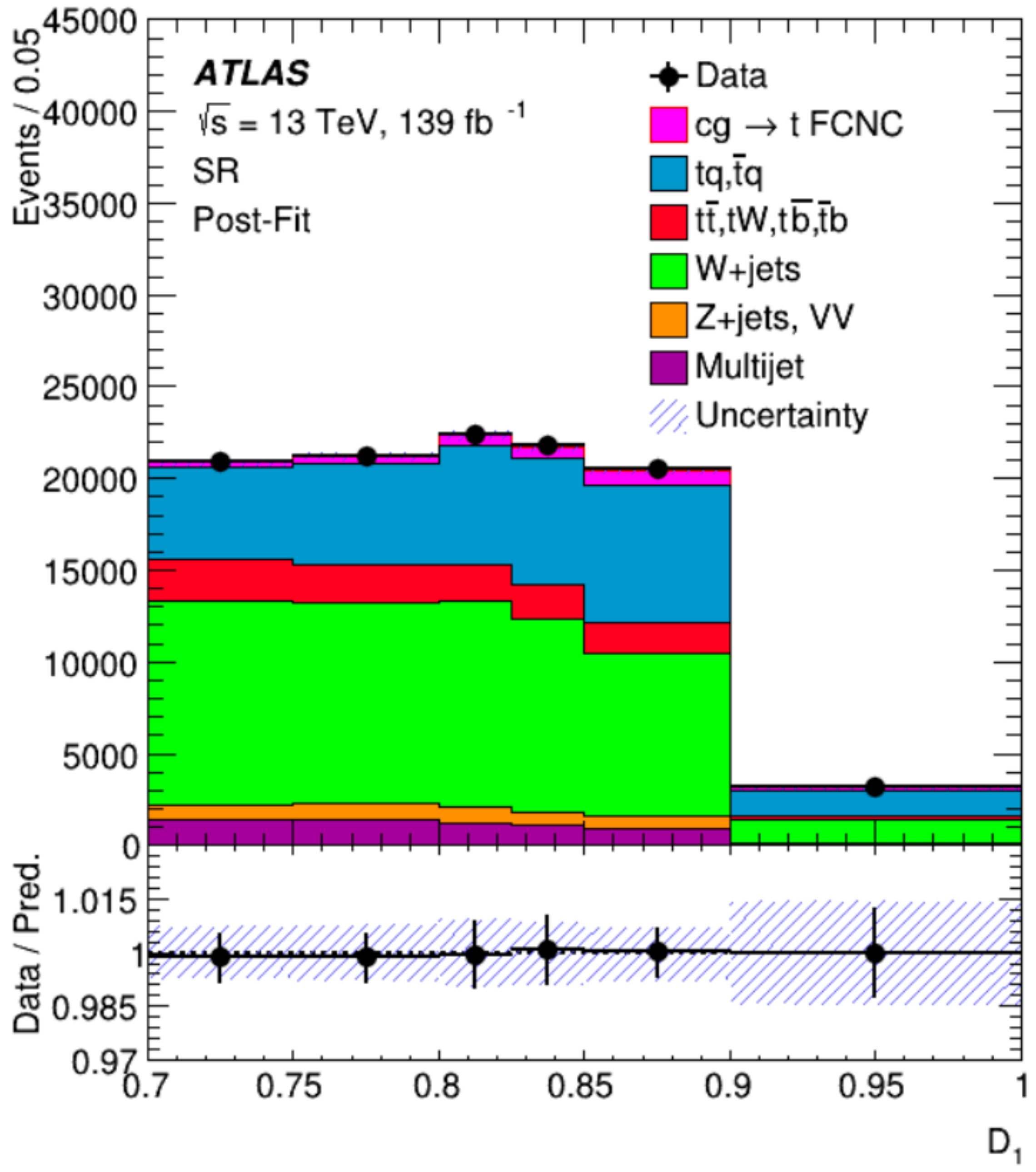
FCNC tqg - selection requirements

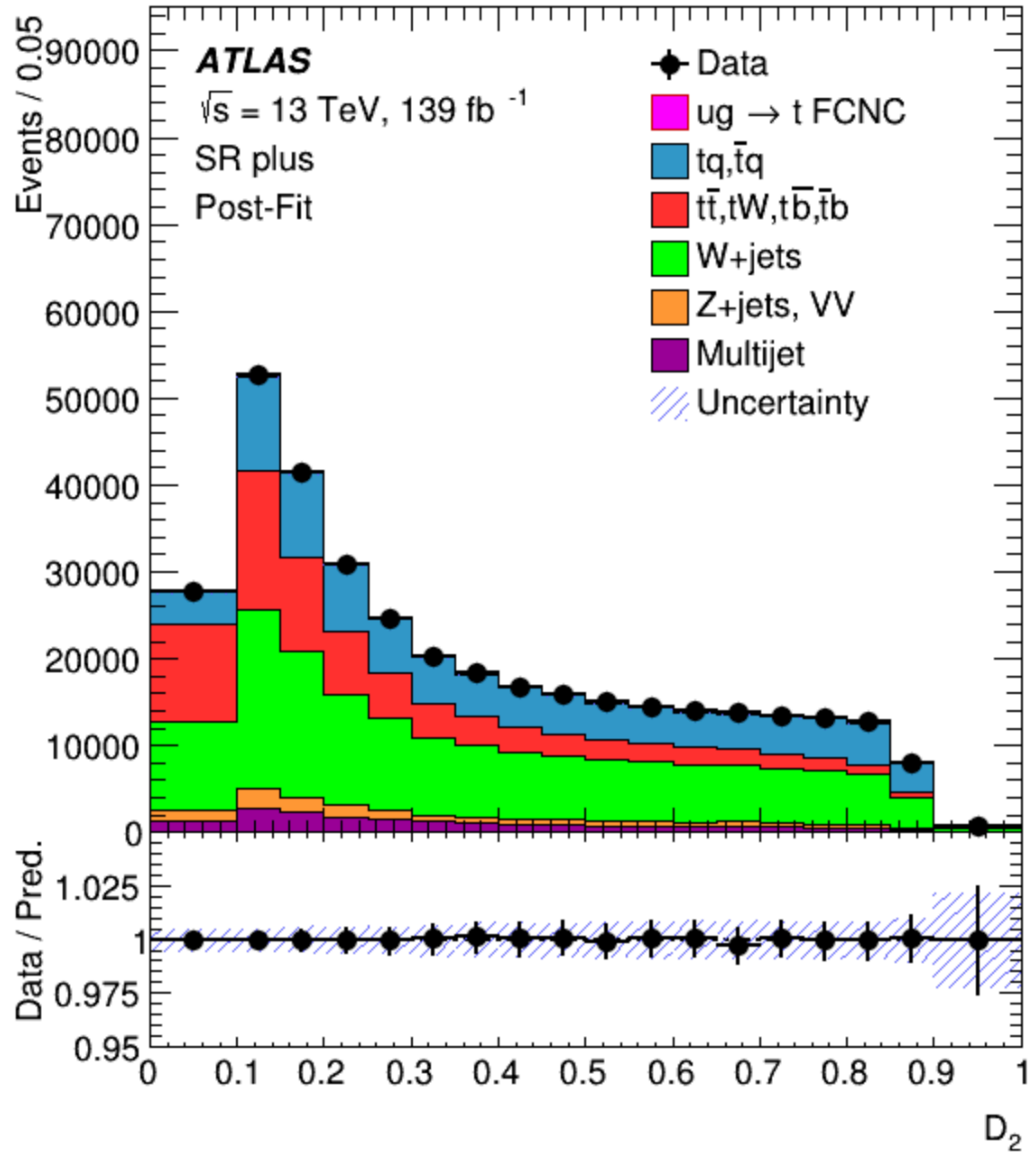
Observable	Common requirements			
$n_{\mathrm{Tight}}(e) + n_{\mathrm{Medium}}(\mu)$	$= 1$			
$n_{\mathrm{Loose}}(e) + n_{\mathrm{Loose}}(\mu)$	$= 1$			
$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 30\,\mathrm{GeV}$			
$m_{\mathrm{T}}\,(W)$	$> 50\,\mathrm{GeV}$			
$n(j)$	≥ 1			
$p_{\mathrm{T}}\,(\ell)$	$> 50\,\mathrm{GeV} \cdot \left(1 - \frac{\pi - \lvert\Delta\phi(j_1,\ell)\rvert}{\pi - 1}\right)$			
	Analysis regions			
	SR	W+jets VR	$t\bar{t}$ VR	tq VR
$n(\lvert\eta(j)\rvert < 2.5)$	$= 1$	$= 1$	$= 2$	$= 1$
$n(b)$	$= 1$	$= 1$	$= 2$	$= 1$
ϵ_b	30%	60% (veto 30%)	30%	30%
$n(\lvert\eta(j)\rvert > 2.5)$	≥ 0	≥ 0	≥ 0	$= 1$
$D_{1(2)}$	–	$0.3 < D_{1(2)} < 0.6$	–	$0.2 < D_{1(2)} < 0.4$

FCNC tqg - postfit discriminants

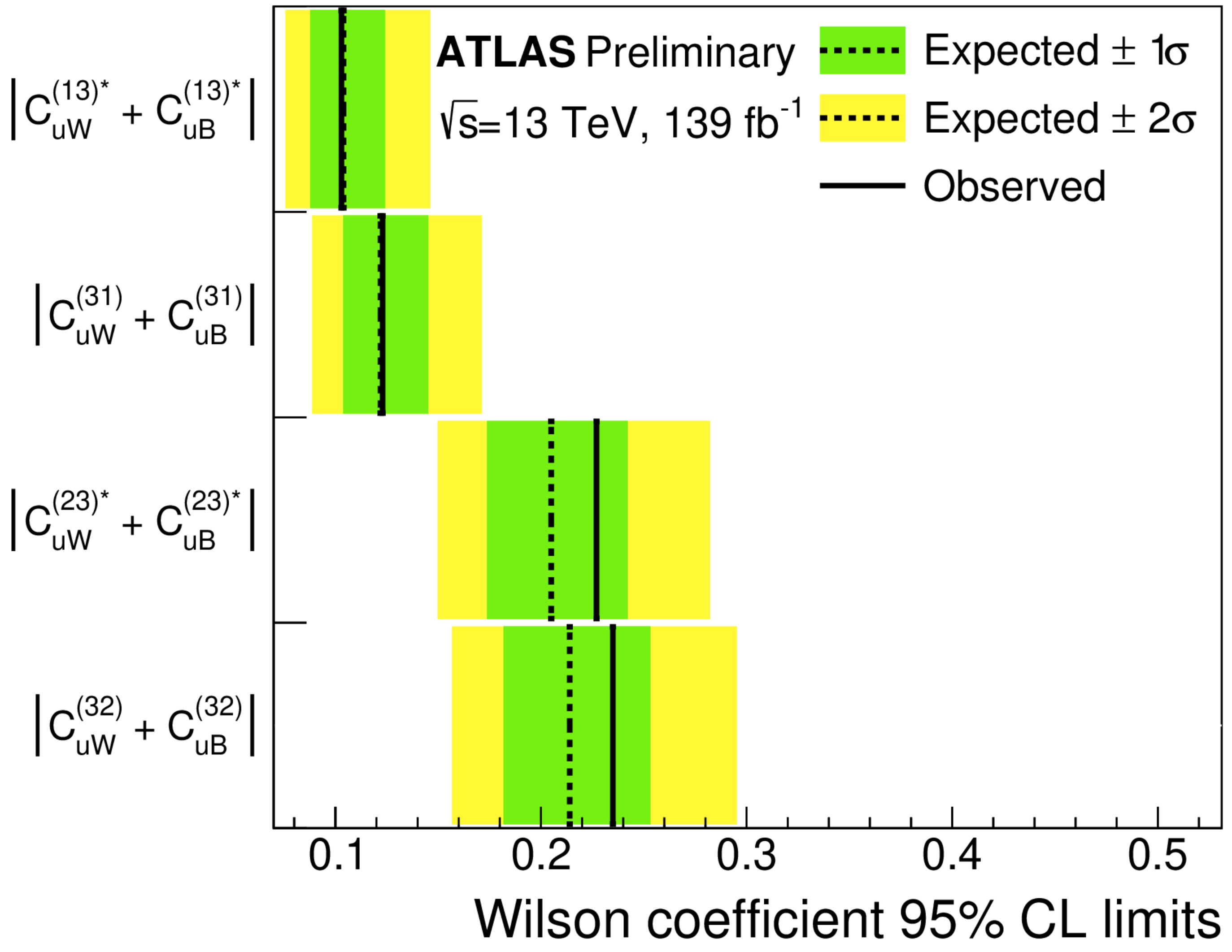


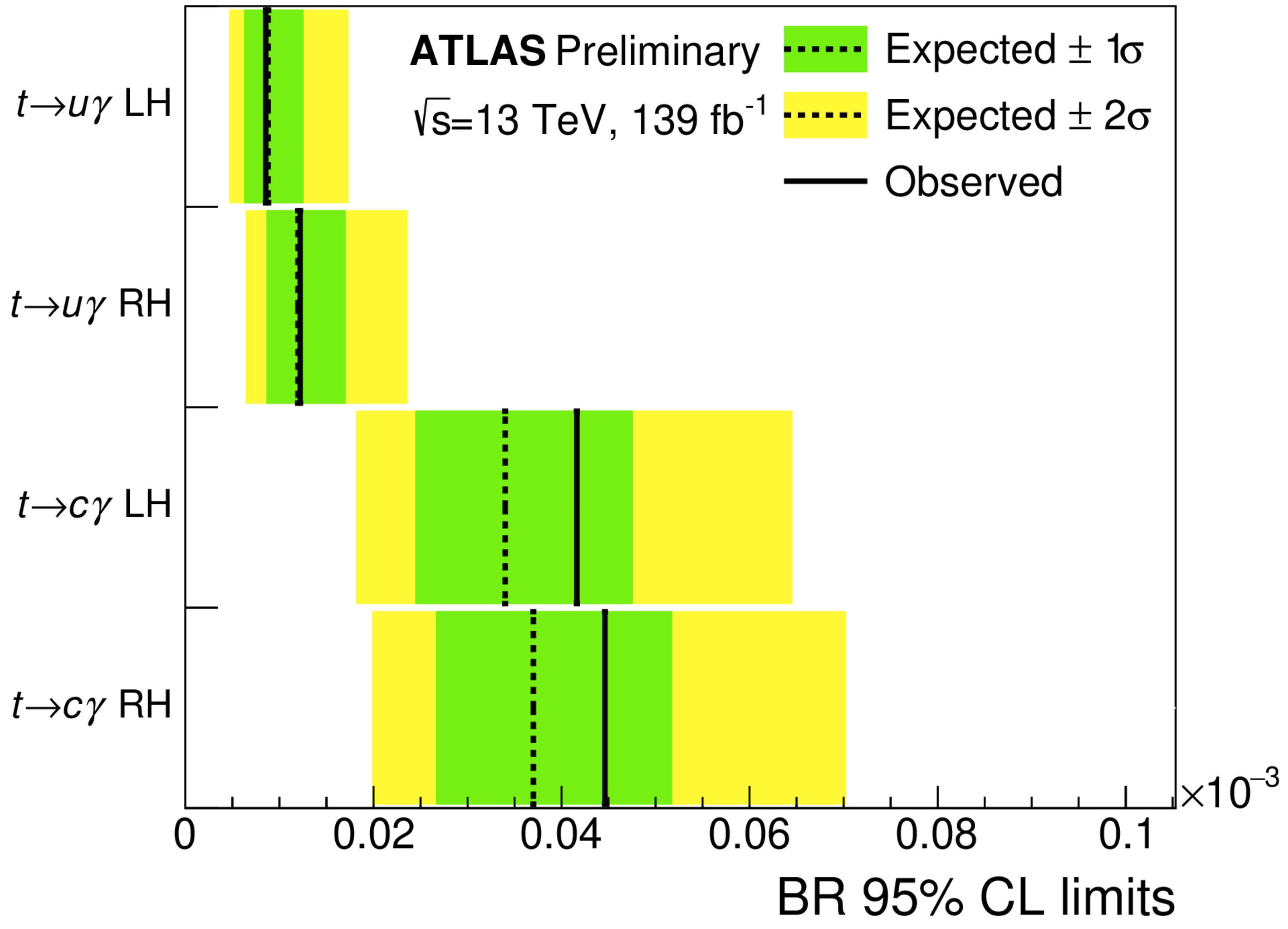






FCNC tqγ - Wilson coeficient and BR limits





Effective coupling	Coefficient limits: Expected	Coefficient limits: Observed	Coupling	BRs $[10^{-5}]$: Expected	BRs $[10^{-5}]$: Observed
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*}\rvert$	$0.104^{+0.020}_{-0.016}$	0.103	$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)}\rvert$	$0.122^{+0.023}_{-0.018}$	0.123	$t \to u\gamma$ RH	$1.20^{+0.50}_{-0.33}$	1.22
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*}\rvert$	$0.205^{+0.037}_{-0.031}$	0.227	$t \to c\gamma$ LH	$3.40^{+1.35}_{-0.95}$	4.16
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)}\rvert$	$0.214^{+0.039}_{-0.032}$	0.235	$t \to c\gamma$ RH	$3.70^{+1.47}_{-1.03}$	4.46

FCNC tqZ - detailed results

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Observable	Vertex	Coupling	Observed	Expected
		SR1+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	9.7	$8.6^{+3.6}_{-2.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	9.5	$8.2^{+3.4}_{-2.3}$
		SR2+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	7.8	$6.1^{+2.7}_{-1.7}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	9.0	$6.6^{+2.9}_{-1.8}$
		SRs+CRs		
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	LH	6.2	$4.9^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZu	RH	6.6	$5.1^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZc	LH	13	11^{+5}_{-3}
$\mathcal{B}(t \to Zq)$ $[10^{-5}]$	tZc	RH	12	10^{+4}_{-3}
$\lvert C^{(13)*}_{uW}\rvert$ and $\lvert C^{(13)*}_{uB}\rvert$	tZu	LH	0.15	$0.13^{+0.03}_{-0.02}$
$\lvert C^{(31)}_{uW}\rvert$ and $\lvert C^{(31)}_{uB}\rvert$	tZu	RH	0.16	$0.14^{+0.03}_{-0.02}$
$\lvert C^{(23)*}_{uW}\rvert$ and $\lvert C^{(23)*}_{uB}\rvert$	tZc	LH	0.22	$0.20^{+0.04}_{-0.03}$
$\lvert C^{(32)}_{uW}\rvert$ and $\lvert C^{(32)}_{uB}\rvert$	tZc	RH	0.21	$0.19^{+0.04}_{-0.03}$

LH: left hand

RH: right hand

← Higher sensitivity from SR2

- Upper limits on branching ratios, were improved with respect to the previous results
  - by factors of 5 (3): LH expected BR limits for t → Zu (t → Zc)
  - by factors of 3 (2): LH observed BR limits for t → Zu (t → Zc)
  - Inclusion of prod. mode, MVA technique, and higher lumi.

FCNC tqZ - predicted and observed yields in SR

	SR1 ($D_1 > -0.6$)	SR2 ($D_2^u > -0.7$ or $D_2^c > -0.4$)
$t\bar{t}Z + tWZ$	137 ± 12	36 ± 6
VV + LF	18 ± 7	24 ± 8
VV + HF	114 ± 19	162 ± 26
tZ	46 ± 7	108 ± 18
$t\bar{t} + tW$ fakes	14 ± 4	27 ± 8
Other fakes	7 ± 8	5 ± 6
$t\bar{t}W$	4.2 ± 2.1	3.1 ± 1.6
$t\bar{t}H$	4.8 ± 0.7	0.89 ± 0.17
Other bkg.	2.0 ± 1.0	2.5 ± 2.9
FCNC $(u)tZ$	0.9 ± 1.7	4 ± 8
FCNC $t\bar{t}(uZ)$	5 ± 9	0.8 ± 1.5
Total background	348 ± 15	369 ± 21
Data	345	380

FCNC tqZ - postfit discriminants

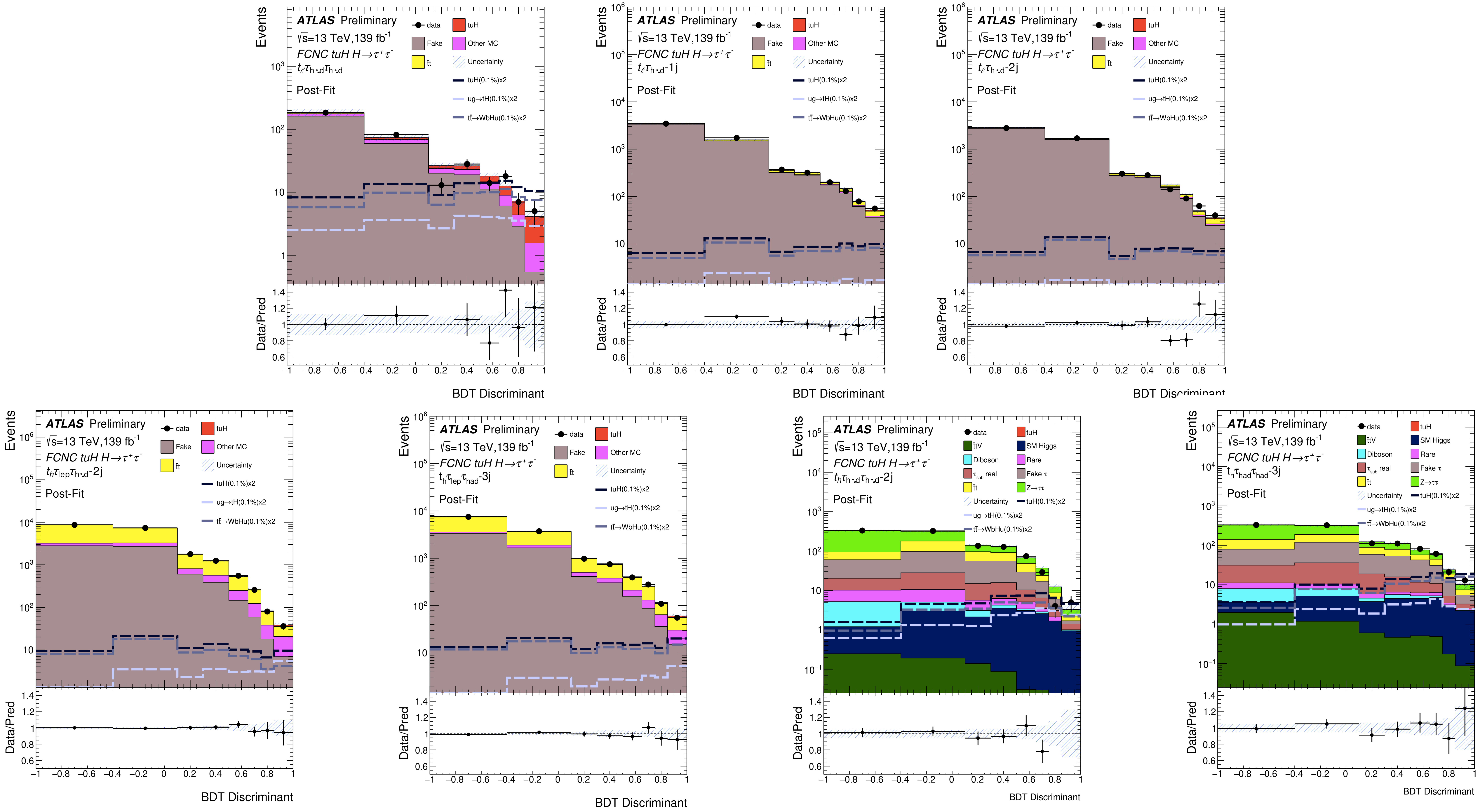
FCNC H → τ + τ - : overview of regions

Regions		b-jet	light flavour jets	lepton	hadronic taus	charge
SR	$t_\ell\tau_{\rm had}\tau_{\rm had}$	1	≥ 0	1	2	$\tau_{\rm had}\tau_{\rm had}$ OS
	$t_\ell\tau_{\rm had}$-1j	1	1	1	1	$t_\ell\tau_{\rm had}$ SS
	$t_\ell\tau_{\rm had}$-2j	1	2	1	1	$t_\ell\tau_{\rm had}$ SS
	$t_h\tau_{\rm lep}\tau_{\rm had}$-2j	1	2	1	1	$\tau_{\rm lep}\tau_{\rm had}$ OS
	$t_h\tau_{\rm lep}\tau_{\rm had}$-3j	1	≥ 3	1	1	$\tau_{\rm lep}\tau_{\rm had}$ OS
	$t_h\tau_{\rm had}\tau_{\rm had}$-2j	1	2	0	2	$\tau_{\rm had}\tau_{\rm had}$ OS
	$t_h\tau_{\rm had}\tau_{\rm had}$-3j	1	≥ 3	0	2	$\tau_{\rm had}\tau_{\rm had}$ OS
VR	$t_\ell\tau_{\rm had}\tau_{\rm had}$-SS	1	≥ 0	1	2	$\tau_{\rm had}\tau_{\rm had}$ SS
CRtt	$t_\ell t_\ell 1b\tau_{\rm had}$	1	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_\ell 2b\tau_{\rm had}$	2	≥ 0	2	1	$t_\ell t_\ell$ OS
	$t_\ell t_h 2b\tau_{\rm had}$-2jSS	2	2	1	1	$t_\ell\tau_{\rm had}$ SS
	$t_\ell t_h 2b\tau_{\rm had}$-2jOS	2	2	1	1	$t_\ell\tau_{\rm had}$ OS
	$t_\ell t_h 2b\tau_{\rm had}$-3jSS	2	≥ 3	1	1	$t_\ell\tau_{\rm had}$ SS
	$t_\ell t_h 2b\tau_{\rm had}$-3jOS	2	≥ 3	1	1	$t_\ell\tau_{\rm had}$ OS

FCNC $H \rightarrow \tau + \tau -$: absolute uncertainties

Source of uncertainty	ΔB [10^{-5}]	
	$t \rightarrow uH$	$t \rightarrow cH$
Lepton ID	0.6	1.0
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.7	0.8
Fake lepton modeling	0.9	1.1
JES and JER	2.4	3.2
Flavour tagging	2.7	3.7
$t\bar{t}$ modeling	2.9	4.3
Other MC modeling	2.1	2.9
Fake τ modeling	3.2	4.6
Signal modeling including $\mathrm{Br}(H \rightarrow \tau\tau)$	5.3	7.0
τ ID	3.3	4.4
Luminosity and Pileup	0.9	1.3
MC statistics	5.1	7.0
Total systematic uncertainty	11.2	15.5
Data statistical uncertainty	14.1	19.6
Total uncertainties	18	25

FCNC H → τ + τ - : tuH - BDT output distributions



FCNC H → τ + τ - : tcH - BDT output distributions